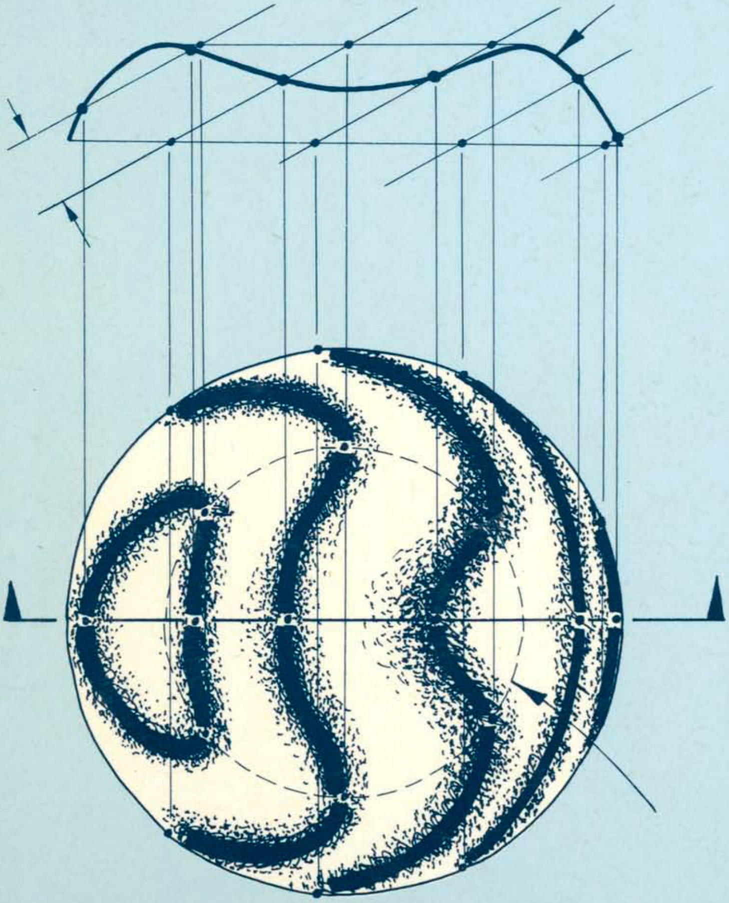
SPIE Volume 472

PRECISION OPTICAL GLASSWORKING

A manual for craftsmen and designers

W. Zschommler

Translated and with additional material by
G. K. Sachdev and J. Maxwell



PRECISION OPTICAL GLASSWORKING

SPIE Volume 472

PRECISION OPTICAL GLASSWORKING

A manual for the manufacture, testing and design of precision optical components and the training of optical craftsmen

W. Zschommler

English translation by G. K. Sachdev and J. Maxwell of *Feinoptik-Glasbearbeitung (Werkkünde fur den Feinoptiker)*

Additional chapters by G. K. Sachdev and J. Maxwell

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Preface to German Edition

The original inspiration for this book is to be found in a series of slide lectures describing the manufacture of optical components in America, which were held before audiences of production engineers in Wetzlar in the post-war years of reconstruction.

Compiled for vocational training purposes, this book on the manufacture of optical components, from simple handwork to modern machine finishing, aims to provide the optical worker and the recently qualified engineer engaged in optics with a much needed companion volume to the many books that exist in the fields of theoretical optics and mechanical engineering.

The description of the fundamentals of optical manufacture is intended to perform the same function as technical lectures for beginners and also for qualified engineers who want to set up modern economic optical production and who cannot do so without an understanding of the work processes. It is a peculiarity of optics, in contrast to mechanical manufacture, that very little is published on the actual work processes. Only comparatively few engineers have a knowledge of optical manufacture, for which the necessary training is customarily obtained only by an apprenticeship in the optical trade. It is therefore a further purpose of this book to present this training in a form suitable for the self-tuition of engineers.

For a further understanding of the work processes in optics it is advisable to consult the German national standard of optics manufacture DIN 3140. This contains many practical hints for the testing of optical parts and also guidelines for maintaining optical manufacturing tolerances, with many manufacturing hints and guidelines for the preparation of the optical drawings that are used in modern industry.

Wetzlar, June 1963 Willy Zschommler

Translators' Foreword

When students of optics, engineers, apprentices, craftsmen and specialist technicians look for books on optical manufacturing in the English language, they find that very few have ever been published and these are mostly out of print. Even when they do manage to find a copy of one of these books in a technical library or preserved lovingly by one of the older craftsmen, they may find the information they require but they do not find a compact textbook that leads them systematically through the various stages of optical component manufacture.

While young workers in the metal-based industries have a number of good textbooks and a range of well organised courses linked to qualifications and a career structure, the trainee in optical manufacturing usually has no such support, and it is our intention in translating, updating and extending this book to help them in this direction by providing a suitable guide book.

W. Zschommler's book *Feinoptik-Glasbearbeitung* stands out in the literature as a very complete, compact, logical and graphic account of the principles and details of both traditional and modern methods of glassworking, as followed for both small quantity and large volume manufacturing.

The late Willy Zschommler had an extensive knowledge of the optical industry and much experience as a teacher of young craftsmen. His book is the result of a number of illustrated lectures for craftsmen and engineers in the optical industry, which have been turned into a profusely illustrated manual of optical glassworking. The subject matter is treated in a systematic and logical fashion and it deals with every aspect of optical component manufacture from basic workshop principles to modern high-speed processing methods such as diamond smoothing and polyurethane polishing. The emphasis at all stages of the book is on the development of economic processing methods matched to the required component tolerances, so that the material is also particularly well suited to the needs of production engineers and workshop foremen.

In translating this book we have not only brought the original text up to date but we have also added a second part, which is an introduction to the detailed specification of optical systems, optical calculations, lens design and the interferometric testing of optical components and subassemblies. We believe that the modern optical technician requires a greater breadth of knowledge than was formerly the case, to meet the sophisticated demands of modern optical manufacturing. It is hoped that this part of the book will encourage the reader to take advantage of the microelectronic revolution, have a go at simple optical calculations and also make more use of the powerful methods of interferometric testing which are so appropriate to the needs of optical manufacturing.

It now gives us particular pleasure to be able to record our thanks to our respective wives, Raj and Janet, for their patient support during our labours of translation, and also to Mrs Shobha Kumar for her help in preparing the manuscript. We would also like to thank the many senior craftsmen, engineers and technicians, unfortunately too numerous to mention individually, with whom it has been our honour to work over the years and for whose successors this book is intended.

January, 1984

G. K. Sachdev, *Dehra Dun, India*
J. Maxwell, *London, England*

PART I:
THE MANUFACTURE OF OPTICAL COMPONENTS

Introduction: Optical Components

The different forms of optical components can be divided into the following categories:

lenses, mirrors and prisms

Lenses can be mainly grouped in accordance with their applications

photographic lenses, telescope lenses, microscope lenses and astronomical lenses

This grouping is convenient from the point of view of manufacture because, in certain situations, particularly when raw materials are being selected or at the time of final inspection, the method of handling has to be different in each case. Further, increasing demands for particular types of optical instrument have changed the manufacturing methods, for example, deep spherical lenses or microscope front lenses which are now being finished out of complete spheres.

Curved mirrors required for optical instruments are found mainly as:

microscope illumination mirrors, search light mirrors
and astronomical mirrors

Of these, the last two are frequently aspheric.

The prisms incorporated in optical instruments are found to be of several different forms, the chief categories being:

Porro prisms of the first type; Porro prisms of the second type;
Dove prisms; pentagonal prisms; roof prisms

and various combinations of these five types.

Prisms belong to the flat surface category, and included in this are other parts of optical instruments such as graticules and plane glass plates, which may be metallised and used as mirrors, or used directly in transmission.

The main testing gauge for the optical worker is the test plate, with which, using the phenomenon of interference, he must check and assess polished surfaces. The inherent accuracy of interference, and the ultimate performance considerations for upholding the surface accuracy, put the highest possible demands on precision in the manufacture of test plates.

The following chapters cover the manufacture of the many different types of optical components mentioned here.

1

Manufacture of Photographic Lenses by the Pitch-pellet Sticking Method (20 operations in accordance with table 1.1)

For the manufacture of photographic optics, two types of objectives are taken into consideration. These differ in their quality requirements and also with respect to their methods of manufacture.

Three- and four-lens component objectives permit low-cost photographic objectives to be manufactured with typical aperture ratios of *f*/6.3, *f*/4.5 and *f*/3.5. The glass for these objectives is received in the form of mouldings or cut pieces, with the usual variation of 0.001 in their refractive indices n_d (n_d is the refractive index measured for the Fraunhofer green–yellow Mercury *d* line, which has a wavelength of 587.6 nanometres). These objectives do not normally need any special recomputing or pairing at the time of assembly, although it is not normally possible to hold close tolerances on focal length.

Four- to seven-component objectives, because of their wide angular field of view and/or high aperture ratio (*f*/2.8, *f*/2 and *f*/1.5), frequently require recalculation for each batch of glass. Because of the requirement for image sharpness on a plane focal surface from this type of objective, the values of n_d for the glass should not be allowed to vary by more than ± 0.00050. It is difficult for the glass melters to hold to such close tolerances, and often one has to use glass with larger deviations; the designer must then make the changes in radii necessary to compensate for the deviation in n_d. Such high aperture lenses are difficult to manufacture because the individual components cannot be interchanged and they have to be processed and stored separately. The optical designer can compute the sensitivity of the system in this respect and should be consulted in such situations.

The two prevailing methods in photographic lens manufacture are the pellet-sticking method (figure 1.1) and the method of sticking to hard block-holding tools

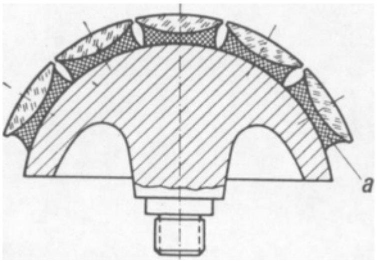


Figure 1.1 Pellet-sticking block holder. *a* Sticking pellet

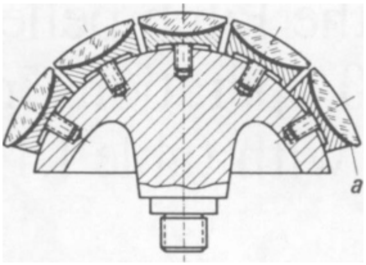


Figure 1.2 Hard block holder. *a* Thin sticking wafer

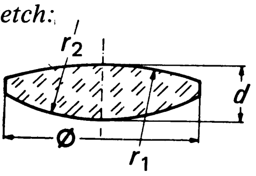
(figure 1.2). The difference between the two methods lies in the method by which the optical components are stuck on the blocking tools. First, a working plan in serial order is described for the pellet-sticking method (table 1.1).

Operation 1: Issue of material

Optical glasses require carefully separated storage according to glass types and, among types, further divisions corresponding to different meltings. The glass catalogues bear the required nominal refractive index values for calculation corresponding to the different types manufactured by each glass works. Every glass delivery is accompanied by a melt slip with the measured glass refractive index data shown on it. The glass works also allocates a serial number for each melting which is stamped on every piece of glass. The melt data slips should be forwarded to the designer so that he can use the measured glass data for his calculations. With this procedure he also has the opportunity to select and match the meltings that are to be used.

With the issue of glass from the glass store, it is useful to make a sample testing of refractive index with a refractometer; this guards against the mixing of glass. The glass pieces should also be checked for impermissible bubbles and striae, according to the drawing and specifications. Before slitting they are prominently marked with a grease pencil so that the defective portions can be rejected during cutting; in doing so it should be borne in mind that glass pieces in which the striae are in the direction of the ray paths can often be used, because they do not

Table 1.1 Plan for manufacture of lenses by the pelleting method

Type of workpiece: *biconvex lens*	*Sketch:*	*Drawing no.:*
		

	Operation	*Department*	*Processing description*
1	Issue of material	Glass store	Glass type: Piece size: n_d tolerance: Piece thickness: Bubble tolerance:
2	Slitting	Milling	Cutting block into slices Slice thickness:
3	Initial grinding	Grinding Milling	Glass plates to be rough ground or milled to size Thickness:
4	Marking and cutting to size	Sizing	Glass plates marked to sizes (squares) and broken Prepared size:
5	Testing of glass pieces	Sizing	Check for bubbles and striae Bubble tolerance: Striae tolerance:
6	Stacking	Blocking	Type of wax: Length of stack:
7	Rounding the stack	Milling	Diameter:
8	Sticking of rounded blanks to block holders (sides 1 and 2)	Blocking	Laying-in shell radius Side 1: Side 2: Block holder radius Side 1: Side 2: Pieces per block Side 1: Side 2: Type of sticking cement Side 1: Side 2:
9	Initial grinding Fine grinding (sides 1 and 2)	Grinding	Grinding radius Side 1: Side 2: Thickness: Type of grinding material:

Table 1.1 *Continued*

	Operation	*Department*	*Processing description*
10	Polishing of block (sides 1 and 2)	Polishing	Radius Side 1: Side 2: Appearance Side 1: Side 2: Interference rings Side 1: Side 2: Type of pitch Side 1: Side 2:
11	Unblocking (sides 1 and 2)	Blocking	Cool down in refrigerator
12	Cleaning	Blocking	Dissolving the residual adhesive material in containers or in ultrasonic chambers Solvent:
13	Centring and edging	Centring and edging	Type of machine: Axis displacement: Diameter: Chamfer size:
14	Chamfering of lenses	Centring and edging	Type of machine: Chamfer size:
15	Testing	Shop inspection	Radii: Appearance: No. of rings: Thickness: Diameter: Chamfer: Centring:
16	Rectification	Polishing	As indicated by the inspector
17	Coating	Vacuum	Antireflection film(s) as specified by the physicist
18	Cementing	Cementing	Type of cement: Axis displacement:
19	Final testing	Final inspection	As per drawing
20	Pairing	Final inspection	As per drawing or test specification

necessarily disturb the image. For bigger lenses and prisms, it is therefore necessary to orient the glass block in the Schlieren test apparatus (figure 1.3) according to the direction of Schlieren (striae) and mark it, so that when the glass is worked it can stay in the appropriate orientation and the worker can cut out the pieces for lenses and prisms in a corresponding fashion.

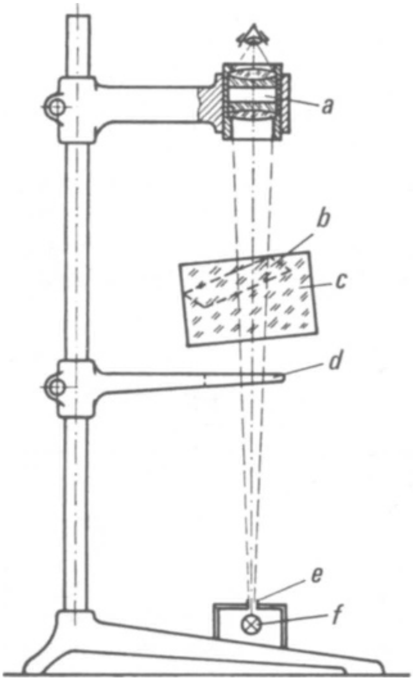


Figure 1.3 Schlieren test apparatus. *a* Wide-angle magnifier, *b* outline of optical component to be generated, *c* glass block, *d* support arm for glass block, *e* pin hole 0.3–0.5 mm diameter, *f* light source

Schlieren (striae) are those inhomogeneous portions of glass that adversely affect the uniform passage of light through them. In optical instruments, glass that has striae across the direction of viewing cannot be used, because the image quality would be adversely affected by this. Larger striae can be easily seen with the naked eye. Finer threads of striae, when held in front of a pin-hole light source, can be seen with the help of an eyepiece. The permissible size of striae should be indicated on the drawing in accordance with the appropriate standards. A preliminary inspection for striae is done in the glass works in front of a mercury lamp.

Operation 2: Cutting glass blocks into slices

As already explained, one can work the lenses from mouldings, or from cut pieces of glass. Because of the cost of the moulding process, it is usually cheaper for a

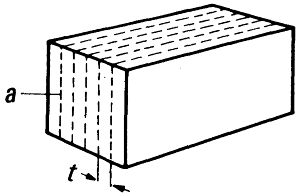


Figure 1.4 Raw glass block. *a* Separating lines, *t* finished thickness plus allowance

new optical system to start with cut pieces of glass. The glass is delivered by the makers in the form of random slabs (figure 1.4).

The slabs are cut into slices with a diamond saw (thickness of slice = finished thickness + 1.5 mm). The construction of a glass-slitting machine is similar to a metal circular saw. The slitting wheel usually has a diameter of about 150 mm, and the glass plate can be pushed against the wheel on the slitting table (figure 1.5).

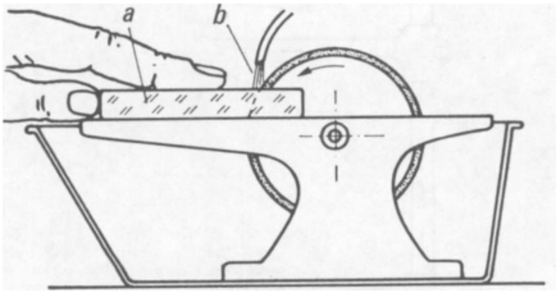


Figure 1.5 Small glass saw. *a* Glass plate, *b* cooling oil supply

When bigger blocks are to be cut into plates, they are rotated against the saw so that one can manage with a saw blade of, at most, 400 mm diameter. The glass block is waxed or mounted on an axis that can be swung in the direction of the saw. The feed occurs with the assistance of a pulling weight, while the block is rotated by hand (figure 1.6).

The slitting wheels rotate at very high speeds; their peripheral velocity is of the order of 25 metres per second. Mineral oil is used as a coolant. Although it is possible to prepare slitting wheels in the workshop by rolling diamond powder into a saw blade, it is advisable to buy sintered blades from specialist manufacturers.

In an emergency, one can slit glass with an iron disc and a plentiful supply of abrasive (and time!).

Operation 3: Plates to be rough ground to size

After slitting, the plates will be found to have deep wheel scuffs, and it is necessary to bring them closer to the finished lens thickness. If necessary, the plates must be

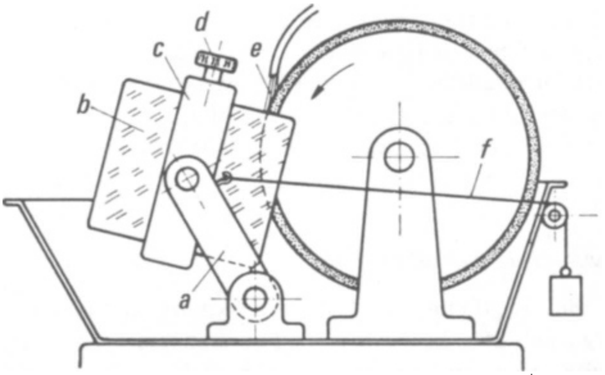


Figure 1.6 Large glass saw. *a* Swinging arm, *b* glass block, *c* rotating holder, *d* clamp for glass block, *e* cooling oil supply, *f* pulling weight

provided with one plane ground surface applied by hand grinding, to enable them to be processed later on block holders. The plates are next waxed on to flat tools (figure 1.7); no high degree of adhesion is required from the wax because the accuracy necessary in the parallel grinding of the plates is not high and, further, because not much heat is generated when compared to that in polishing. It suffices if the plates are cemented with some paraffin wax. The plates are next ground against a flat iron tool on a machine with a supply of rough abrasive to bring them to a finished thickness + 0.3 mm (figure 1.8).

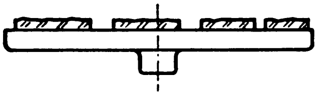


Figure 1.7 Glass plates waxed on a flat block holder

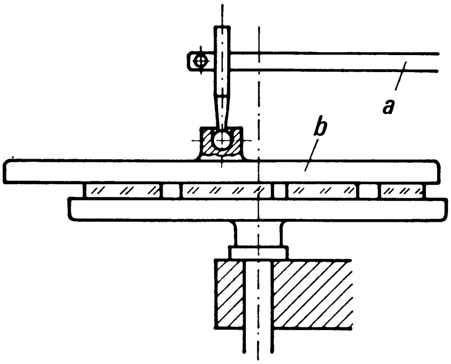


Figure 1.8 Flat block holder on lever-arm grinding machine. *a* Lever arm of the machine, *b* flat iron grinding tool

Because both the sides are to be surface ground, it is necessary to rewax them for the second side; a tolerance of 10 angular minutes of arc (1 mm in 300 mm) is usually sufficient for parallelism. After grinding, the glass plates are removed from the iron tool by mechanical shock and then soaked in a solvent bath of methylated spirit, caustic soda or trichlorethylene to dissolve the remnants of wax sticking to them.

Milling plates with diamond milling tools

Instead of free abrasive grinding, the plates can be more economically worked with diamond impregnated tools. In this case the two waxing processes may be avoided, and the parallelism is achieved directly from the machine. First, on a flat diamond impregnated surfacing tool, one side of the plate is flattened as shown in figure 1.9: the plates are held against a fence and are abraded by the pressure of their own weight, or with additional pressure from the hand.

Next, the flattened side is laid on the vacuum chuck of a vertical milling machine fitted with a diamond tool, and the second side is worked to bring it to the required thickness (figure 1.10). Mineral oil is continuously supplied during the process.

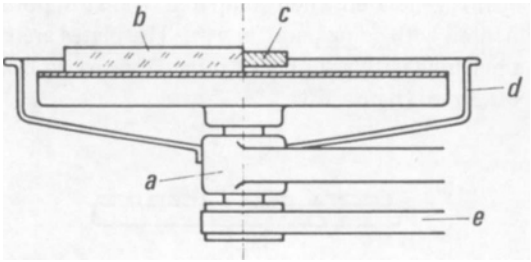


Figure 1.9 Flat milling diamond disc. *a* Bearing of milling disc, *b* glass plate, *c* fence, *d* bowl for spray protection, *e* drive pulley

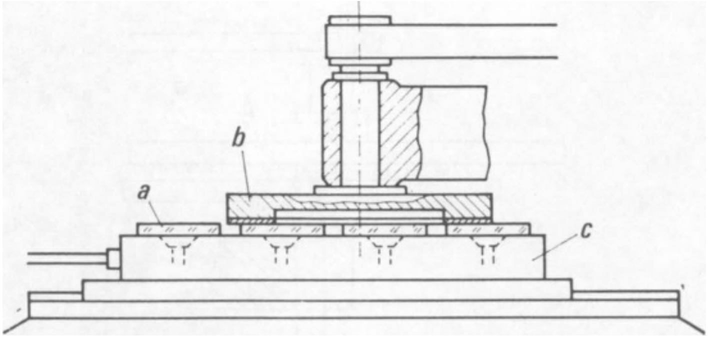


Figure 1.10 Vertical milling machine with diamond tool. *a* Glass plate, *b* diamond milling disc, *c* vacuum chuck

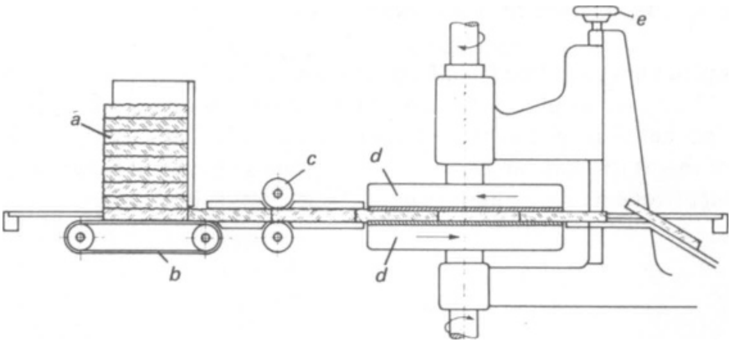


Figure 1.11 Automatic transport for the milling of plates. *a* Stacked glass plates, *b* transport strip, *c* transport rollers, *d* diamond milling discs, *e* adjustment for diamond discs

A combination of both these machines, that is, simultaneous parallel milling of both sides, can be achieved in an automatic double-sided milling machine. In mass production the glass plates are milled continuously between the milling discs (figure 1.11).

Table 1.2 clarifies the terms 'grinding' and 'milling'.

Table 1.2 Grinding and milling

Operation	*Tool*	*Machine*
Metal finishing		
Grinding	Bonded grinding wheels	Cylindrical and surface grinding machine
Milling	Toothed tools of high-speed steel or with hard metal tips	Horizontal and vertical milling machines
Optical finishing		
Grinding	Loose grains on grinding shells	Lever-arm grinding machines
Milling	Diamond charged tools	Special diamond milling machines and also lever-arm grinding machines can be used

Operation 4: Marking and cutting plates to size

The glass plates are placed on a marking table and scribed to size with a glass cutter (figure 1.12). Next, the plate is laid on a finishing table and with the stroke of a hammer the individual pieces are separated (figure 1.13). The scribed line is laid on a nylon or catgut filament, and the hardwood plank so positioned that the force of the hammer stroke works on both sides of the separating line on the glass.

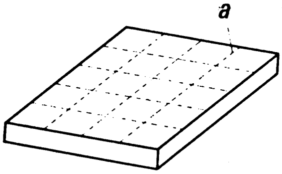


Figure 1.12 Scribed glass plates. *a* Separating lines

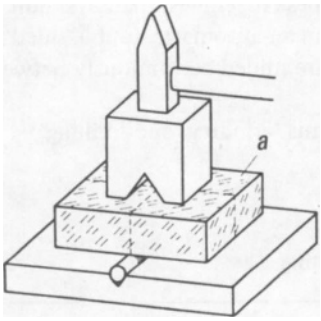


Figure 1.13 Parting with hammer strokes. *a* Glass piece

The blank sizes have to be made according to the diameter and surface radii of the finished lenses. The longer the radii of the surfaces, the more difficult it is to centre and edge the worked lens (see operation 13, centring of lenses). Thus in the case of long radii, the blank size should be larger and in the case of thicker plates, an extra allowance has to be added for the possibility of edge fractures.

For photographic lens components of typical radii and thickness, the sizes of the cut-out pieces can be as shown in table 1.3.

For diameters above 30 mm, it is advisable to make octagonal pieces, in order to save tool wear and process time in the initial rounding. In view of the high price of glass, the allowance provided should not be larger than necessary.

Economised scribing and parting

The method just described for breaking glass plates into pieces is slow, laborious and not particularly accurate, and it may be considerably speeded up by the

Table 1.3 Size of cut-out pieces for photographic lens components

	Allowance on diameter (mm)	
Finished diameter (mm)	*for disc cut pieces*	*for square cut pieces*
3–10	1.0	2.0
10–20	1.5	2.5
20–30	2.0	3.0
30–40	2.5	3.5

provision of a scribing guide such as is shown in figure 1.14 and a foot-operated breaking press.

As shown in figure 1.14 the scribing guide scores lines up and down the plate by traversing a hardened knife wheel along the guide *d*. For each line that is scribed the guide bar is located in a new slot on the diagonal spacing bar *f*. The spacing bar may be set at any angle to space the scribed lines at the required separation and the scale *g* is calibrated directly in strip widths. The guide bar *d* is fitted with end stops so that the wheel cutter does not run over the edge of the glass plate, and the glass plate is locked into position on the table with the eccentric clamp *i*.

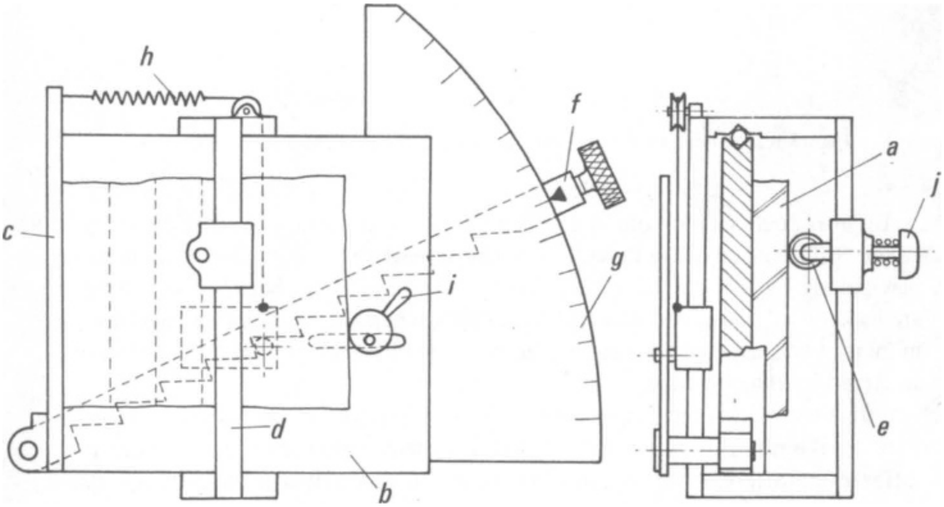


Figure 1.14 Marking table. *a* Glass plate, *b* table, *c* datum fence, *d* guiding bar for the hardened scribing roller, *e* hardened scribing roller, *f* diagonal notch strip for spacing the scribed lines, *g* scale for spacing adjustment, *h* tension spring for automatic latching of the guiding bar, *i* knob for clamping the glass plate, *j* knob for pressing the scribing roller

Instead of a hammer a small foot-controlled eccentric press may be used for breaking the scribed plates. The anvil of the press is fitted with a breaking block made of hardwood or some suitable fibrous material.

Operation 5: Checking cut pieces for bubbles and striae

The broken edges of the cut pieces are clear, and it is therefore possible to check them for bubbles and striae. This can be done in front of a 60 watt lamp, with the help of a magnifying eyepiece (figure 1.15). The final mouldings must also be checked for stress, with the help of a polarising viewer. Striae in mouldings can be detected by the examiner, but usually only with difficulty.

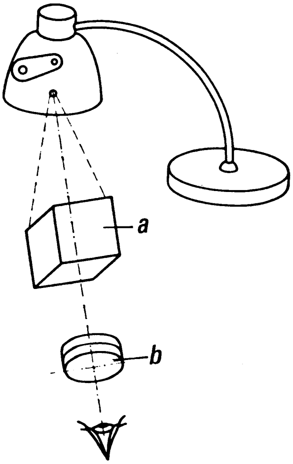


Figure 1.15 Checking the raw glass pieces. *a* Job being checked, *b* magnifier

By introducing a pin hole of about 0.5 mm, the detection of striae becomes easier. Still more sensitive detection can be achieved with dark-field illumination, particularly by viewing the border between dark and bright backgrounds. Bubbles are usually only cosmetic defects, particularly when they are neither large nor numerous enough to influence significantly the intensity of light transmitted or scattered by the objective.

Striae and stress cannot usually be tolerated in photographic objectives because they are the result of inhomogeneities and consequently the refractive index is different in different portions of the lens, which adversely affects the image quality. Testing all optical parts should be done according to appropriate national or international standards. If the drawings of all the optical components of an optical instrument are marked with the standardised symbols, then the work of optical inspection becomes less ambiguous.

Operation 6: Making stacks of cut pieces for initial rounding

The glass pieces that have been found good on examination are waxed together to form a stack and these stacks are further waxed to centred, mechanical end pieces. The stacking can be best achieved in a V-block (figure 1.16).

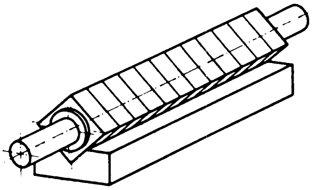


Figure 1.16 Waxing in a V-block

Operation 7: Rounding the stack of cut pieces into a cylinder

The stack is held between the centres of a cylindrical grinding machine and rounded into a cylinder. On one of the waxed end pieces is screwed a dog or catch which is used to rotate the stack in the direction opposite to that of the carborundum wheel and, by further longitudinal to and fro traverse, the stack is reduced to the required diameter (figure 1.17).

In the case of glass this operation is generally called milling. It is so similar to metal grinding that a normal cylindrical grinding machine can be used for the purpose. The speed of longitudinal to and fro traverse of the table has to be chosen according to the type of glass material. An oil–water mixture can be used as a lubricant.

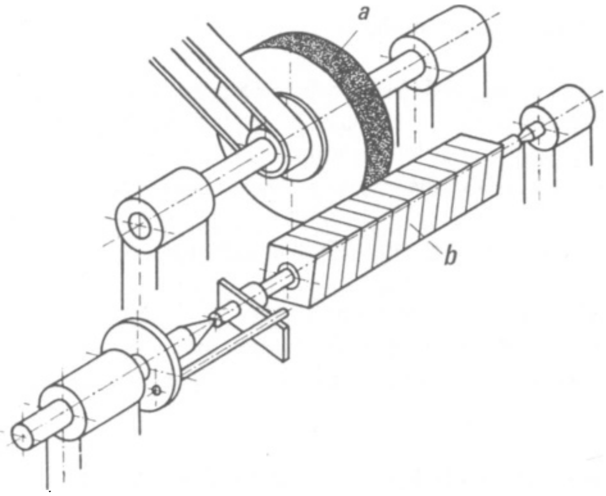


Figure 1.17 Cylindrical grinding machine. *a* Carborundum wheel, *b* stack of blanks

The cylindrical diameter should be chosen according to the final diameter plus an allowance for centring and edging. For further processing, it is also necessary that the roll should be cylindrical within ±0.05 mm. After rounding, the roll is decemented and the discs are cleaned in a solvent to remove the adhesive sticking to them.

For economical large-scale production, operations 6 and 7 can be completed on one special grinding machine. In this event, the individual glass pieces are not waxed together, but are pressed together so that they can withstand the pressure of the diamond cutting wheel. The cutter rotates so that the cutting forces act in a longitudinal direction on the glass roll (figure 1.18). The diameter of the rolls can be obtained to within very close limits. The machine works automatically, and hence one worker can operate several machines. Mineral oil is used as a lubricant.

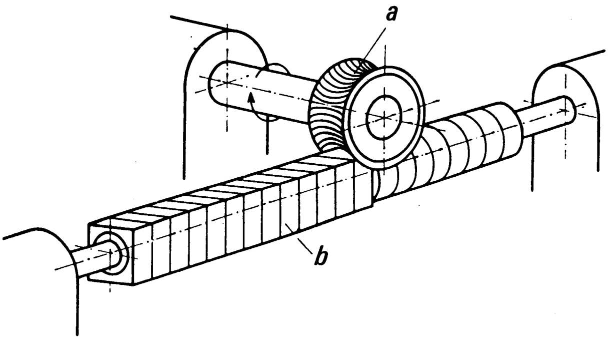


Figure 1.18 Working direction of milling on a roll-rounding machine. *a* Diamond miller, *b* stack of blanks

Operation 8: Sticking blanks on the block holder

The operation of blocking lens blanks will be described for the three forms of lenses normally encountered in the majority of photographic lenses (figure 1.19). For economical production of lenses, blanks should be blocked together in the largest possible numbers and then worked. The individual operations are as follows:

Calculation of the radii of the block holder and of the laying-in shells (figure 1.20).
Covering the blanks with pellets (figure 1.21).
Laying the blanks on the laying-in shell. Some adhesive wax is uniformly rubbed on the laying-in shell so that the blanks do not slip and strike each other (figure 1.22).

The block holder should be heated so that is just melts the pellet pitch (60–70°C). The block holder is lowered on to the back of the pelleted blanks.

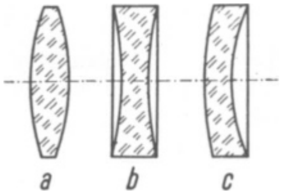


Figure 1.19 Usual lens types. *a* Biconvex. *b* Biconcave. *c* Convexo–concave

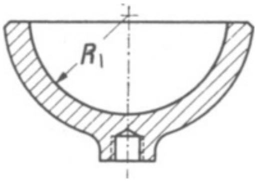


Figure 1.20 Laying-in shell. R_1 Laying-in radius

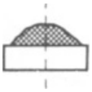


Figure 1.21 Blank with pellet of backing pitch

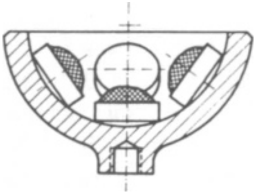


Figure 1.22 Blanks in the laying-in shell

Beforehand, three equally spaced steel balls are positioned to obtain a uniform gap between the shell and the block holder. The heat of the block holder melts the pellet pitch and so the blanks stick to the block holder and are 'frozen' in place when the block is cooled with water (applied with a sponge) (figure 1.23).

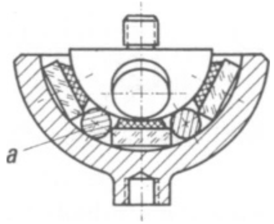


Figure 1.23 Sticking pelleted components to block holders. *a* Balls for spacing

Calculation of radii for block holders and laying-in shells

As an example consider the grinding and polishing of a double convex lens (figure 1.24). The glass pieces have been cut to size and rounded, giving cylindrical glass discs of 30 mm diameter (figure 1.25) which have been rough ground parallel to a thickness of 5.3 mm in operation 3.

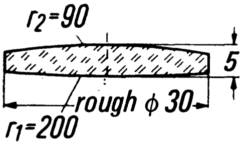


Figure 1.24 Biconvex lens

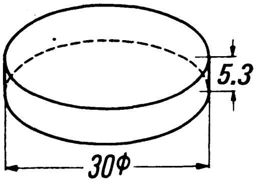


Figure 1.25 Blanks for biconvex lens

It is estimated that 0.15 mm of material will be removed during the roughing, fine grinding and polishing of each surface, and therefore the thickness will finally be reduced to 5.0 mm. Experience suggests that the shallower surface ($r = 200$ mm) should be worked first, and the block holder should be chosen to be as large as possible for economic production. In the case of hemispherical blocks, the included angle of the lenses should not exceed 85°, otherwise the grinding marks (grey) on the edge of the lenses at the periphery of the block will be difficult to polish away (figure 1.26).

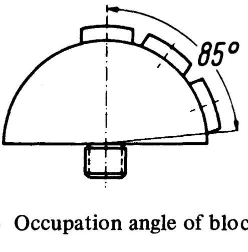


Figure 1.26 Occupation angle of block holder

The radius R_1 of the laying-in shell for flat discs of diameter 30 mm, prior to grinding them to a radius of $r = 200$ mm, can be calculated with the help of the

Pythagoras Theorem (figure 1.27).

$$R_l = \sqrt{(\text{radius to be ground})^2 + \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{200^2 + 15^2} = 200.56 \text{ mm}$$

The radius of the corresponding block holder does not have any effect on the accuracy of the surface being ground because the intermediate pitch adjusts itself according to the space and it may be chosen as approximately R_b = 192 mm.

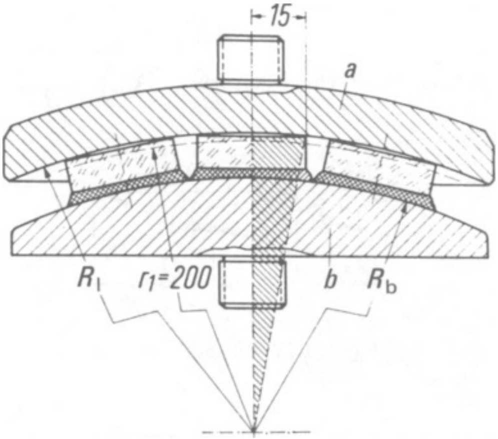


Figure 1.27 Blocking for the first side of a biconvex lens. *a* Laying-in shell, *b* block holder

Similarly, for the finished radius of r_2 = 90 mm on the other side of the lens, (figure 1.28) we have

$$R_l = \sqrt{(\text{radius to be ground})^2 + \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{90^2 + 15^2} = 91.24 \text{ mm}$$

and the corresponding radius for the block holder can be taken as approximately R_b = 83 mm.

That the shallower side of the lens should be the first to be worked is only appropriate when the thickness tolerance is more than ± 0.1 mm. When the thickness has to be more accurate, for example, within ± 0.02 mm, then the shallower side should be worked last, because it is easier and quicker to obtain accurate thickness with blocks holding larger numbers of lenses.

As a further example consider the grinding and polishing of a biconcave lens (figure 1.29). Again the blanks are rounded to a diameter of 30 mm. The thickness of the glass piece is so chosen that the appropriate edge thickness can be obtained

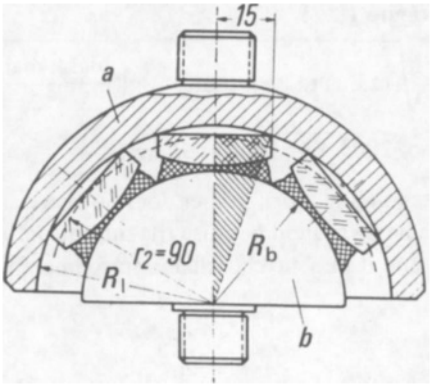


Figure 1.28 Blocking for the second side of a biconvex lens. *a* Laying-in shell, *b* block holder

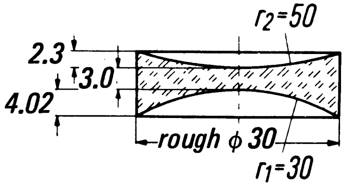


Figure 1.29 Biconcave lens

and this means that the sags of the r_1 = 30 mm curve and the r_2 = 50 mm curve must both be added to the centre thickness. We must also add 0.15 mm for the working of each surface, so the blanks are to be prepared to a total thickness of 9.62 mm. In the manufacture of double concave lenses, the laying-in shell also becomes a block holder and thus its radius has to be calculated precisely.

If a radius of 30 mm is to be ground on a blank with a diameter of 30 mm, then from figure 1.30 we obtain using the Pythagoras Theorem

$$\text{auxiliary quantity } X = \sqrt{r_1^2 - \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{30^2 - 15^2} = 25.98 \text{ mm}$$

and with the known thickness of the blanks, the radius of the laying-in shell can therefore be calculated as

$$R_1 = \sqrt{(X + \text{blank thickness})^2 + \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{(25.98 + 9.47)^2 - (15)^2} = 38.49 \text{ mm}$$

where we have taken one of the 0.15 mm working allowances off the blank.

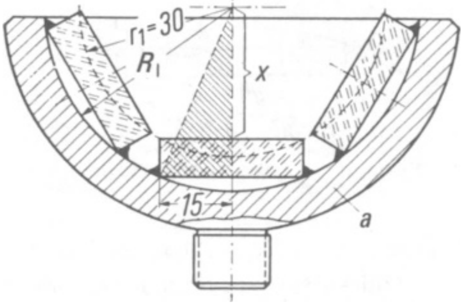


Figure 1.30 Waxing the first side of the lens to the shell. *a* Laying-in shell = blocking shell

Similarly for the second side of the lens (r_2 = 50 mm) as shown in figure 1.31:

$$\text{auxiliary quantity } X = \sqrt{r_2^2 - \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{50^2 - 15^2} = 47.69 \text{ mm}$$

and so the radius of the laying-in shell in this case is

$$R_1 = \sqrt{(X + \text{blank thickness})^2 + \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{(47.69 + 9.32)^2 + 15^2} = 58.95 \text{ mm}$$

where now we have taken the second 0.15 mm working allowance off the blank.

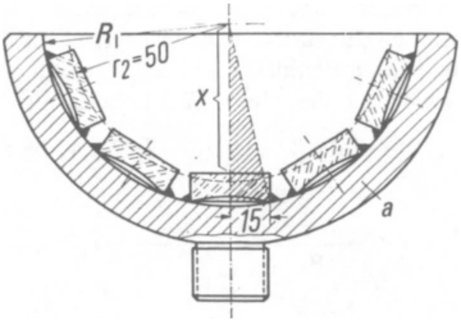


Figure 1.31 Waxing the second side of the lens to the shell. *a* Laying-in shell = blocking shell

As a third example a convexo–concave lens form is chosen. This is often found in photographic objectives of all types, and a working sketch is shown in figure 1.32. The glass pieces are cut to size and ground to a diameter of 30 mm; the thickness for the blank is again chosen so that the required edge thickness is obtained and this means that the sag of the concave side of radius 30 mm is to be added to the centre

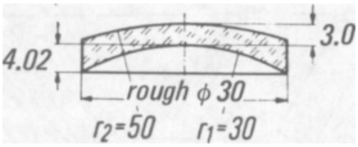


Figure 1.32 Convexo–concave lens

thickness. As before, an additional working allowance of 0.15 mm for each side is necessary, so that the total thickness of the blank in this case amounts to 7.32 mm.

For the manufacture of these types of lens, experience suggests that it is better to work the concave side first and in this case again the laying-in shell is also the block holder, so its radius must be calculated. If on a blank of 30 mm diameter, a radius of 30 mm is to be ground (figure 1.33) then the radius of the laying-in shell is obtained as before as

$$R_1 = \sqrt{(X + \text{blank thickness})^2 + \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{(25.98 + 7.17)^2 + 15^2} = 36.38 \text{ mm}$$

where here again, as in the second example

$$X = \sqrt{r_1^2 - \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{30^2 - 15^2} = 25.98 \text{ mm}$$

For the grinding of the second (convex) side the radius of the block holder must also be calculated as it is on this surface that the edges of the polished concave side will be blocked to obtain a centre thickness of 3.0 mm after grinding the 50 mm radius (figure 1.34). Here again the value of X is to be calculated. It is given by

$$X = 50 - (3.0 + 4.02) = 50 - 7.02 = 42.98 \text{ mm}$$

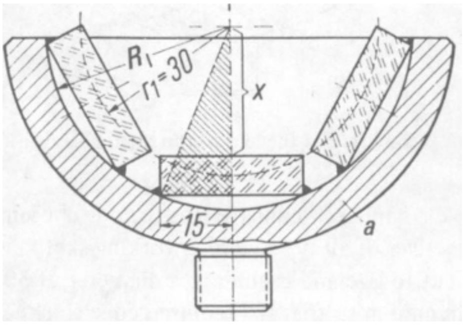


Figure 1.33 Waxing for the first side of a convexo–concave lens. *a* Blocking shell

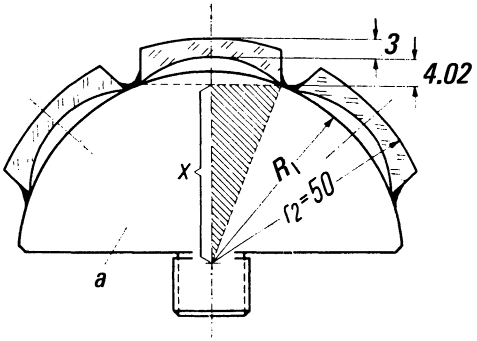


Figure 1.34 Waxing for the second side of a convexo–concave lens. *a* Convex blocking tool

and from this is obtained the radius of the block holder

$$R_1 = \sqrt{X^2 + \left(\frac{\text{blank diameter}}{2}\right)^2}$$

$$= \sqrt{42.98^2 + 15^2} = 45.52 \text{ mm}$$

In this case a convex tool is to be used as the block holder.

If, for the manufacture of lenses from blanks, their thicknesses and diameters are given, then for manufacturing by the pelleting method, one can calculate the radii of block holders and laying-in shells with the help of the scheme in figure 1.35, for all forms of lenses. However, one has to remember that the thickness tolerances of the blanks have already been compromised by any inaccuracy in the calculation of their sag values. For thickness tolerances greater than ±0.2 mm, one can use the sag nomogram given in figure 1.36, but for more reliable results the formula

$$\text{sag} = R - \sqrt{R^2 - \frac{D^2}{4}}$$

should be used. In a fully controlled process, after the first side is finished and before the second side is blocked, the lenses are ground parallel to improve their centration and to make them all equally thick. For this process an extra allowance of nearly 0.3 mm is given for the working of both sides.

For this parallel grinding, before blocking the second side, the finished sides of the blanks are waxed on to a flat, clean plate. The flat plate is warmed until the wax melts and then the blanks are laid on it and carefully pressed into contact (figures 1.37 and 1.38). After cooling, the flat block is ground parallel.

In this way the blanks are ground closer to their specified thickness, and experience indicates that an extra 0.02 to 0.03 mm over and above the maximum permissible thickness should be retained. The final grinding of the flat surface

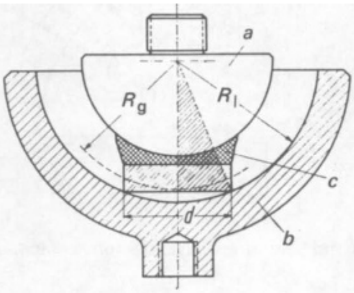
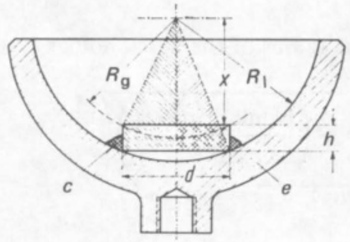
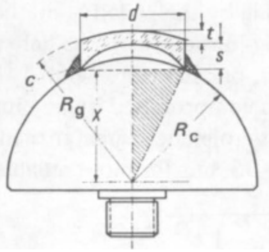
Blocking radius calculation	*Sketch*	*Formula*
Concave shell for the preparation of convex blocks For the processing of biconvex lenses, sides 1 and 2		$R_l = \sqrt{R_g^2 + \left(\frac{d}{2}\right)^2}$
Concave blocking shell for the preparation of concave blocks For the processing of biconcave lenses, sides 1 and 2		$X = \sqrt{R_g^2 - \left(\frac{d}{2}\right)^2}$ $R_l = \sqrt{(X+h)^2 + \left(\frac{d}{2}\right)^2}$
Convex blocking for the preparation of convex blocks For the processing of a convex surface as a second side and simultaneously obtaining the correct lens thickness		$X = R_g - (t + s)$ $R_c = \sqrt{X^2 + \left(\frac{d}{2}\right)^2}$

Figure 1.35 Scheme of calculation of block holder radii for the pellet-sticking method. *a* Block holder, *b* concave setting shell, *c* cement, *e* concave blocking shell, *s* lens surface sag, *t* centre thickness of lens

should be finished with the finest abrasive, and should even be rough polished in the case of thickness tolerances such as 0.01 mm, because the gradually diminishing flat patch that is observed while grinding the second side serves as a witness for grinding to the correct thickness. All the lenses on the block holder serve as guides for the achievement of the required thickness and any errors of grinding radius or centration will be obvious and may be corrected in subsequent process cycles.

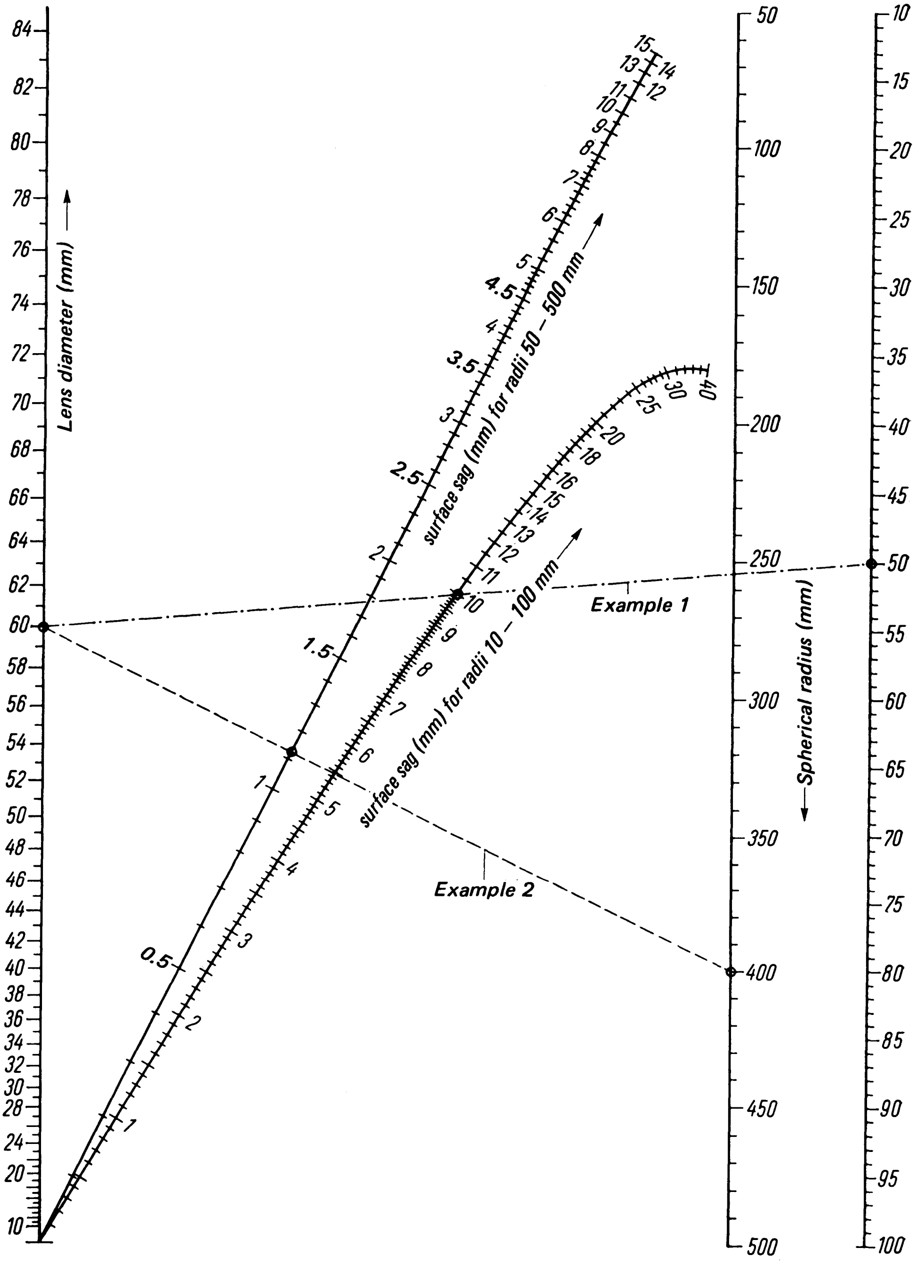


Figure 1.36 Sag curves. (1) Lens diameter 60 mm, $r = 50$ mm gives sag = 10 mm. (2) Lens diameter 60 mm, $r = 400$ mm gives sag = 1.1 mm

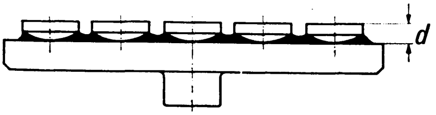


Figure 1.37 Waxing convex first sides for truing. *d* Finished centre thickness plus extra allowance

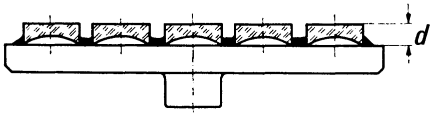


Figure 1.38 Waxing concave first sides for truing. *d* Finished edge thickness plus extra allowance

Operation 9: Rough and fine grinding of lenses on block holders

The blanks waxed on the block holders have flat surfaces which have to be converted to either a concave or a convex curve. This is done by using an iron shell tool of a radius corresponding to the roughed radius required, plus an allowance according to the type and particle size of abrasive used. The abrasive is mixed with water and fed between the glass components and the grinding shell and in this way the glasses are initially rough ground (figure 1.39).

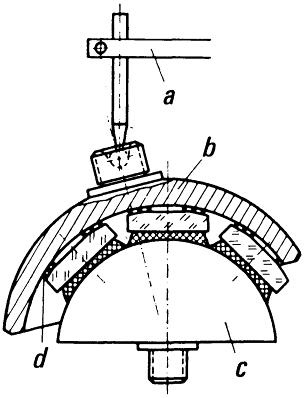


Figure 1.39 Rough grinding of a block of lenses held on pitch pellets. *a* Lever arm of the machine, *b* iron shell tool, *c* block holder, *d* abrasive grains

For roughing, coarse grades of abrasives are used and for blanks worked on convex block holders, the initial grinding shell can have a radius equal to that of the original laying-in shell. In the case of concave blocks, these should be ground with a shorter radius tool than the final lens surface radius.

Further details are now given for grinding with different abrasives and the selection of witness diameters that are appropriate to each stage. Roughing with coarse and medium abrasives is done with a number of grinding shells and is continued until a 1 mm diameter flat witness patch remains.

Comparison of the witness diameter sizes over the complete block shows whether the different grinding shells used one after the other are correct, or whether the shells have changed in radius because of usage. In this way the optician uses these witness marks for guidance in obtaining the correct lens thickness and simultaneously maintaining the radius of the tools.

As soon as the last signs of the witness patches disappear, one must change to the finest abrasive. From roughing, up to the stage before polishing, can usually be accomplished in three steps, with three types of successively finer abrasives. The block holders that are occupied up to a nearly hemispherical form must usually be ground in four or five steps. For very large radii, one can if necessary achieve all the steps of grinding and fine grinding on one grinding shell. However, as one reaches the finer abrasives the shell will bite at the centre, and tend to produce decentred components and also require longer process times, so it is usually better to use more than one tool radius.

In the case of nearly hemispherical blocks, one should never attempt the roughing on a shell meant for fine grinding, because in this situation the progressive change in radius during grinding would destroy the all-important edge contact condition.

The process of initial coarse grinding requires the sensitivity of the human hand for proper control and must therefore be done individually by hand, while the finer grinding is mostly carried out with the commercial lever-arm grinding machines which provide a smooth and consistent working pressure.

The loose abrasive grinding process

For economic working, starting with blanks or mouldings, it is desirable to obtain the smooth ground lens surface in the shortest possible time. In practice this means that it is necessary to remove the surplus material as quickly as possible. In the case of mouldings it may be necessary to remove 0.5 mm, owing to surface irregularities. In any case, the extent of further removal of glass in steps at each grinding stage should be firmly laid down. By experience it has been found to be mostly to the extent shown in figure 1.40.

In the process of grinding, the outer layers of glass are fractured and crushed by the harder grinding material and it is necessary to use grinding materials with the largest possible grain size to maximise the speed of cutting. If one is to begin work with diamond tools, then the radius to be milled or generated should be equal to the roughing radius. In the case of the use of an abrasive between the glass and an iron shell, there must be sufficient space between the glass and the iron for the abrasive particles, that is, the difference between their radii should correspond to the grain size of the abrasive. Clearly, the radius of the grinding shell for convex

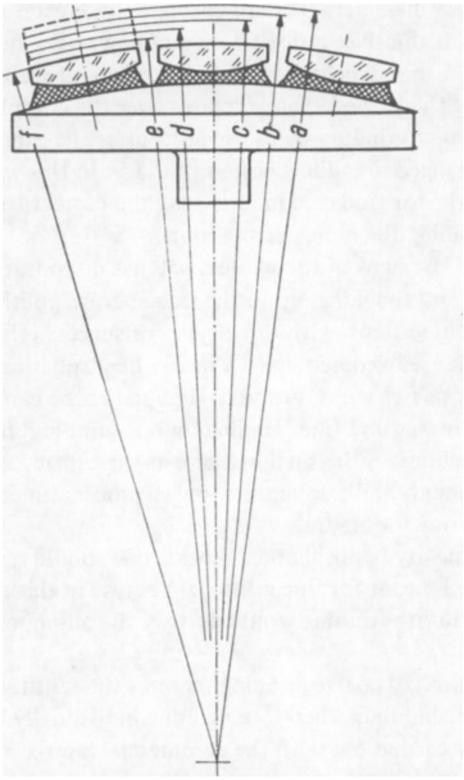


Figure 1.40 Example for grinding steps. *a* Mould radius = 100.6 mm, *b* milled and roughed radius = 100.15 mm, *c* medium ground radius = 100.1 mm, *d* fine ground radius = 100.05 mm, *e* finest ground radius = 100.02 mm, *f* finished radius = 100.00 mm

block holders must be larger, and for concave block holders smaller than the required radius by an amount equal to the grain size of the emery (figures 1.41 and 1.42).

The maximum grain size used in optical processing has an average diameter of 0.25 mm. For the values taken in the example of figure 1.40, we can see that to obtain a roughed radius of 100.15 mm on a convex block, the concave grinding

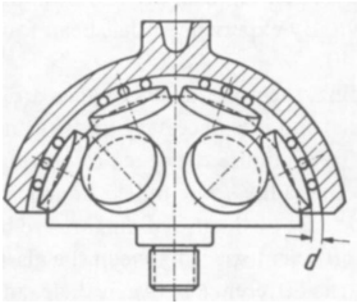


Figure 1.41 Radius addition for concave shells. *d* Difference in radii = grain size

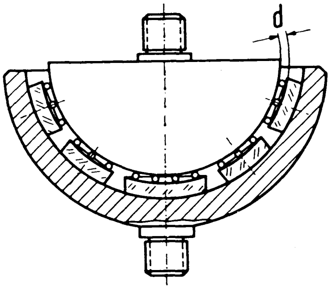


Figure 1.42 Radius deduction for convex shells. *d* Difference in radii = grain size

shell to be used must have a radius of 100.15 + 0.25 = 100.40 mm, while on the other hand, for obtaining a roughed radius of 99.85 mm on a concave block, the convex grinding shell must have a radius of R = 99.85 – 0.25 = 99.60 mm.

We will now follow this example, which has been started with roughing, and take it to medium and fine grinding and calculate the radii of the grinding shells corresponding to the grain sizes of each of the different types of abrasive used. Usually, between the roughing and medium grinding steps another initial grinding step is introduced so as to reduce the total grinding time. It is of course always attempted to use that abrasive in fine grinding that leaves behind only the finest grinding marks, so that one gets as near as possible to the polished surface texture. The selection of the type of abrasive is made after careful trials, measurements and observation. The grains of the medium grinding emery have an average diameter of 0.03 mm and, therefore, to obtain a medium ground radius of 100.10 mm on a convex block holder, the concave grinding shell must have a radius of R = 100.10 + 0.03 = 100.13 mm. On the other hand, for a medium ground radius of 99.9 mm on a concave block holder, the necessary convex grinding shell must have a radius of R = 99.90 – 0.03 = 99.87 mm.

The abrasive grains required for the purpose of fine grinding have an average thickness of 0.01 mm, so for obtaining a fine ground radius of 100.05 mm on a convex block, the concave grinding shell must have a radius R = 100.05 + 0.01 = 100.06 mm, and for obtaining a fine ground radius of 99.95 mm on a concave block holder, the necessary convex grinding shell must have R = 99.95 – 0.01 = 99.94 mm.

The finest grinding particles have a diameter of 0.007 mm and the convex and concave surfaces required have radii of 100.02 and 99.98 mm respectively, and this leads to the choice of tool radii as 100.027 and 99.973 mm respectively.

Finally, it should be said that, because every craftsman has his own way of grinding and also because the different abrasives, machines and machine settings all influence the final result, it is necessary to determine the desired radii for the different steps of grinding by practical trial, keeping the grain size of the different types of abrasives used in view as a scientific guide, in the fashion described above.

Table 1.4 gives data found by experience, depending on the radius to be ground.

Table 1.4 Radii of grinding shells for different stages of grinding, relative to the finished radius

Grinding radius (mm)	*Stage of grinding, radius increment in mm*				
	Finest grinding	*Fine grinding*	*Medium grinding*	*Initial grinding*	*Rough grinding*
r up to 30	0.01	0.04	0.08	0.12	0.30
$r = 30–60$	0.02	0.05	0.10	0.15	0.35
$r = 60–100$	0.03	0.06	0.13	0.20	0.40
$r = 100–150$	0.05	0.09	0.22	0.35	0.52
$r = 150–200$	0.08	0.12	0.34	0.50	0.70
$r = 200–300$	0.12	0.28	0.50	0.80	1.00

The details given in table 1.4 are appropriate for loose abrasive grinding only. In the case of machine milling, because of its dependence on diamond laps, there are other factors to be considered for the choice of surface radius at each stage and for the corresponding correction of the fine grinding shell. In the case of the pellet-sticking method, the blocks can only rarely be milled with diamond tools because the height of each of the blocks as measured from the threaded shoulder datum will vary outside acceptable limits.

Correction of grinding shells

The necessary radius variations corresponding to the different types of abrasives used must be checked and established so that each successive shell bites the block from the edge (figure 1.43). The radii required for rough, initial, medium, fine and finest grinding stand in a direct relationship to one another and the practical optician finds out this relationship and the interdependence of the grinding shells using his skill and experience.

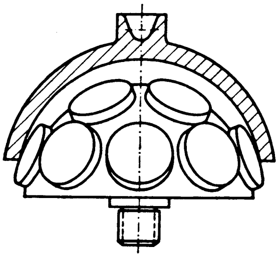


Figure 1.43 Edge bite of the grinding shell

In each specific situation he estimates from the feel of the rubbing contact of opposite shell pairs how they should be corrected to 'bite' from the edge. In the case of mass production, the radius steps corresponding to the action of the different grades of abrasive must be chosen so that the grinding marks of the previous coarser abrasive are removed in the shortest possible time.

Table 1.4 shows that with increase of radius, so the increments in radius also grow. In this discussion, however, we have only considered the type of wear that would result from simple hand working, where the effects of the rotating spindle of the lever-arm machine have no influence. What in fact happens when both the reciprocating and the rotating motions are involved in the wearing process is that longer radius grinding tools are worn relatively more in the centre than are short radius tools, and this effect also has to be taken into account in the adjustment of the tools during production working.

The most important correction of grinding shells must be done for that of the finest grinding, because in this case the precise radius increment (measured in interference bands) that has to be maintained for polishing must be taken into account.

As has been explained, the correction of grinding shells has to be done by the sensitive detection of relative frictional forces, because it is only with the help of this that the required accuracy can be achieved. It is not possible for machine milling or turning of the shells to achieve the required absolute radius accuracy and the job of correcting grinding shells is guided by test plates. If we take the case of a lens of diameter 50 mm and surface radius 100 mm (convex or concave), which on finished polishing should show no interference band, that is, it should have exactly the same radius as the test plate, then according to experience, after the finest grinding the test plate should show two interference rings so that the polishing shell makes the appropriate initial edge contact (figure 1.44).

During the grinding process, the grinding shells are continuously wearing, so they must be adjusted to maintain two interference rings in this way. The fine adjustments required for this purpose would be impracticable on a radius turning lathe and the optician therefore does the final correction of the grinding shells himself. The best possible spherical shell obtained from the metal machine shop

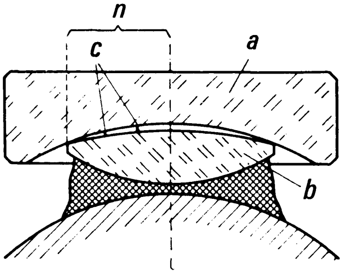


Figure 1.44 Appropriate radius increment after final grinding. n Number of interference rings from centre to edge = 2, a test plate, b lens, c occurrence of interference rings

is lap-ground by the optician, and polished enough so that, by placing a damp test plate on it, interference rings can be seen.

In cases where the test plate gives edge contact and shows too many interference rings, for example, eight rings (figure 1.45), then some material has to be removed from the centre of the grinding shell, that is, its radius has to be made shorter. For this purpose the grinding shell is screwed on to a machine spindle and then, with a handtool, a file, or a piece of used carborundum wheel, some material is removed from the centre of the shell (figure 1.46). In the case when the test plate shows centre contact (figure 1.47), this is not beneficial and some material has to be removed from the edge of the shell (figure 1.48). In the example the case of a convex lens has been taken, but similarly a concave lens can be considered and again the correction has to be done by the sense of feel in exactly the same way.

If the shell is deformed on account of erroneous mounting on the metal machine tool, or through the bad handling of the correction by the optician, then the shell may be mounted above or below its mate on a lever-arm machine and lapped with smooth and regular oscillations (figure 1.49).

In the case of mass production, it is particularly important to rectify worn or deformed tools to avoid disturbance in the flow of production, and it is important to appreciate that their deviation from the required form in the course of use can be opposed by the appropriate adjustment of the grinding machine so that the wear of the surface is evenly distributed.

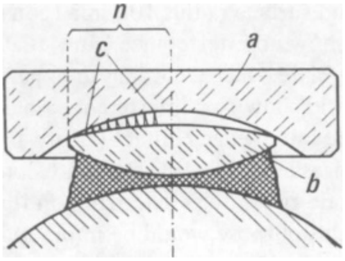


Figure 1.45 Unacceptably large radius increment (edge contact). *n* Number of interference rings from centre to edge = 8, *a* test plate, *b* lens, *c* occurrence of interference rings

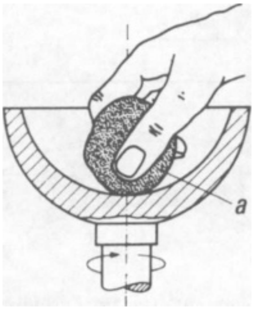


Figure 1.46 Shell correction in the centre. *a* Piece of carborundum

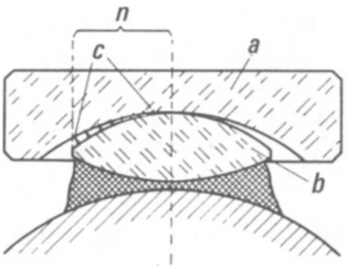


Figure 1.47 Unacceptably large radius increment (centre contact). *n* Number of interference rings from centre to edge = 8, *a* test plate, *b* lens, *c* occurrence of interference rings

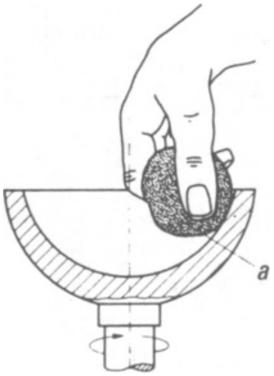


Figure 1.48 Shell correction at the edge. *a* Piece of carborundum

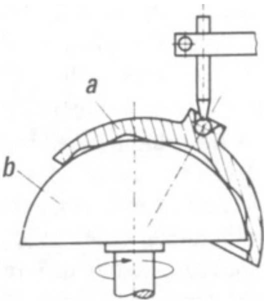


Figure 1.49 Corrective lapping of grinding shells. *a* Deformed grinding shell, *b* opposite shell

As has already been explained, the polishing shell should 'bite' the smoothed block from the edge and in this way the smoothing must be so conducted that when a test plate is put on the polished surface interference rings appear to move in from its edges, that is, the test plate must start contact at the edge. The number of interference rings to be maintained at the smoothing stage depends on its radius, the permissible error of the finished lens, and on the angular occupation of the block.

In photographic optics, as a rule, a band error of one to three interference rings is allowed at the final polishing stage; the corresponding error for the smoothing stage, recommended according to experience, is given in table 1.5.

Table 1.5 Band error deviation for the smoothing worker

Pieces per block holder (occupation of the block holder)	*Permissible band error (number of interference rings) in smoothing for radii*					
	up to 20 mm	20–40 mm	40–60 mm	60–80 mm	80–100 mm	above 100 mm
1	7	6	5	4	4	3
Up to 4	6	5	4	4	3	2
Up to 8	5	4	3	3	2	1
Up to 14	4	3	2	2	1	1
Up to 30	3	2	1	1	1	0.5
Up to 60	2	2	1	1	1	0.5

Operation of grinding and polishing machines

The glass lenses and block holders covered with glasses are ground on machines which, through regular to and fro lapping with the grinding shells and with the supply of abrasive, are worked as evenly as possible. The to and fro and rotating movements are so overlapped that all areas of the glass surface are covered and abraded by the grinding shell in an irregular repetition. The usual arrangement is that the to and fro movement of the grinding shell is actuated by an eccentric moving lever, while the block that is to be ground is made to rotate on the machine spindle. The speeds of the strokes of the eccentric, and of the rotating spindle should be different, and further should also not be any simple ratio or multiple of one another. The optical machines supplied by different manufacturers all have almost the same types of moving elements (figure 1.50).

No particularly high degree of accuracy is required from the sliding contacts and the movements of optical machines when compared with metal working machine tools, because the tool and the job run unconstrained with respect to one another. It is, however, of importance to the optician to know how the to and fro movement and the sizes of the shells produce their effect on the work when it is mounted on the spindle or moved by the lever arm, because with this knowledge it is possible for him to produce work to interference accuracy. In the universal applications of the simple lever-arm machine, the optician must exercise considerable ingenuity

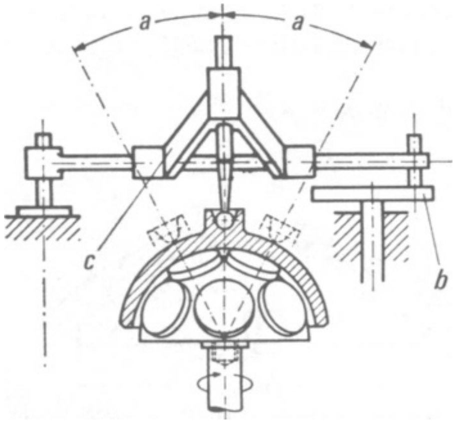


Figure 1.50 Schematic diagram of front view of lever-arm machine. *a* Path of ball pin, *b* eccentric, *c* lever arm of machine

and skill to achieve various results. When the movements of the machine have been adjusted for grinding only one type of job, then even relatively unskilled assistants can produce good results if they have learnt how to maintain the correction of grinding shells.

The optician learns about the operation of grinding machines from experience and by his sense of feel, and from their working and performance he appreciates the important aspects of their operation. The performance is seen with the help of the test plate and the important features of the machine action are the different adjustments of the stroke length of the lever-arm movement (figure 1.51), the ratio

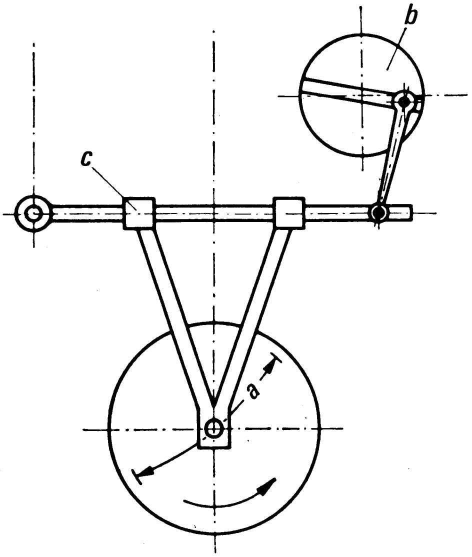


Figure 1.51 Schematic diagram of top view of lever-arm machine. *a* Path of ball pin, *b* eccentric, *c* lever arm of machine

of shell size to job size (figure 1.52), the arrangement of the job on the spindle (figure 1.53) or under the lever arm (figure 1.54) and the preliminary correction of the grinding shells.

All these features of the process of grinding are interdependent and must be

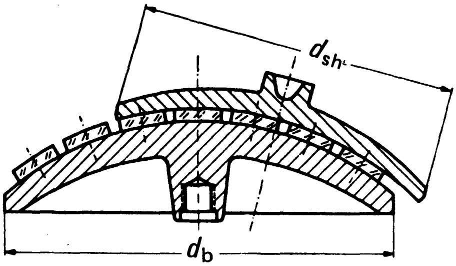


Figure 1.52 Ratio of shell diameter to block holder diameter. d_{sh} Shell diameter, d_b block holder diameter

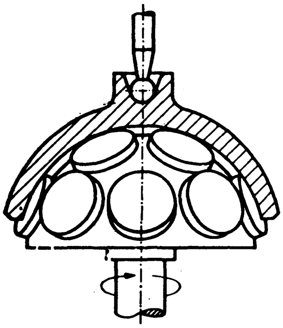


Figure 1.53 A block of lenses held on the spindle below the grinding tool

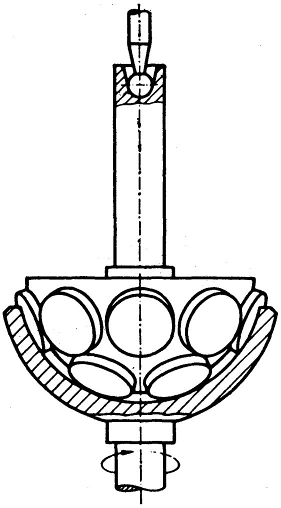


Figure 1.54 A block of lenses under the lever arm held above the grinding tool

clearly understood by the optician if he wants to change the final surface shape in a deterministic fashion.

Effects of different adjustments on grinding machines

Because the effects are interdependent in a rather complicated way, each effect can only normally be observed in the situation where the adjustment of a particular motion is made to its extreme setting. According to the setting of the eccentric drive, the ball pin that drives the grinding shell or the block holder covers a longer or shorter to and fro path. In the case where the machine is adjusted for normal grinding movements, the ball pin moves symmetrically to both sides of the block holder and hence the shell goes beyond the edge of the lens block. The block holder gets evenly worn (figure 1.55) and so the optician can progress the ground block on to any one of the already mentioned finer steps of grinding. In this case the grinding shell is only a little smaller than the block holder.

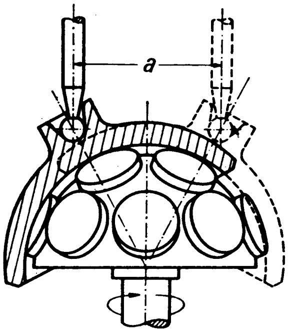


Figure 1.55 A block of lenses on the spindle, working with even bite. *a* Normal movement of the pin

We may now apply a simple descriptive argument to analyse the action of a grinding or polishing machine. In this analysis it is important to remember that the block holder is firmly driven by the machine, while the tool rotates with the block holder only as the result of friction. We will consider the arrangement shown in figure 1.55 which represents the simplest state of adjustment of the action, in which case the wear is more or less evenly distributed over the surface. To see this, we consider one stroke of the eccentric crank and one rotation of the workpiece. During roughly one-third of the time the situation is as shown in figure 1.56, and wear occurs on the edges of the work by virtue of the rotation of the workpiece (the centre of the block being more or less stationary because it lies on the axis of rotation). During roughly another third of the time there is no relative motion at all between the tool and the work, because the tool spins with the work, and this is represented by figure 1.57. Finally, there is the effect of the eccentric pin driving the tool over the centre of the workpiece (which can be regarded as stationary for

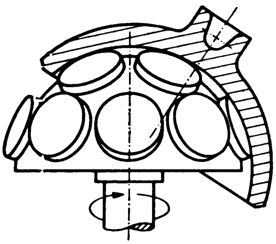


Figure 1.56 A block of lenses on the spindle: the grinding shell spends nearly one-third of the grinding time of every stroke on the edge

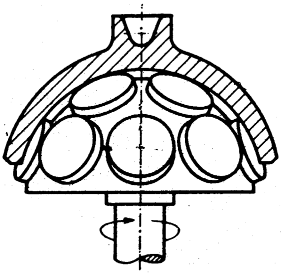


Figure 1.57 Block holder on the spindle and the grinding shell in the centre: nearly one-third of the running time of every stroke is like this, with no relative motion between the tool and the lenses

this part of the argument), while the dragged rotation of the tool reduces the relative motion at the edges of the block (figure 1.58).

Clearly the quantitative mathematical analysis of this situation is a formidable task, especially when it is remembered that this is but one of an infinite set of adjustment conditions and tool to workpiece diameter ratios. It is the mastery of this subtle and complex situation that is the basis of the practical optician's skill.

By restricting the path of the ball pin to one side of the block holder and by using a tool of approximately two-thirds of the work diameter, as in figure 1.59,

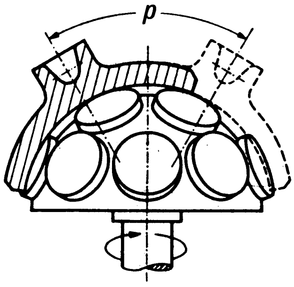


Figure 1.58 Block holder on the spindle; grinding shell goes over the centre; nearly one-third of the grinding time of every stroke is like this. *p* Path of the shell over the centre

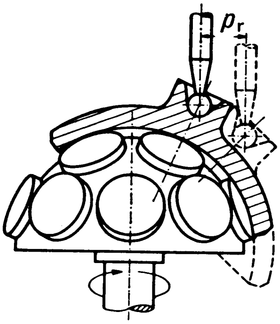


Figure 1.59 Block holder on the spindle; excessive edge bite. p_r Restricted path of the pin

one can emphasise the grinding effects at the edge of the work. In this case the progress of the grinding is slowed down, but the effect on the radius of the work is significant, although the state of correction of the grinding tool does not need to be particularly precise. The mechanism of this process may be understood by reference to the analysis of the normal grinding situation; clearly in this case, however, the situations represented by figures 1.57 and 1.58 no longer occur and we are left only with the situation of figure 1.56.

These methods also clearly depend on the location of the work holder, that is, whether it is driven by the machine spindle or moved to and fro by the ball pin. In the two examples described, the block was driven by the spindle, but it can happen that the grinding shell is driven, while the block holder runs unconstrained with it, and again, by setting equal movement of the ball pin on both sides of the spindle one gets the normal grinding effect, wearing the edges and the centre nearly evenly; so, by correcting the grinding shells appropriately, the optician progresses the work rapidly to finer abrasives (figure 1.60).

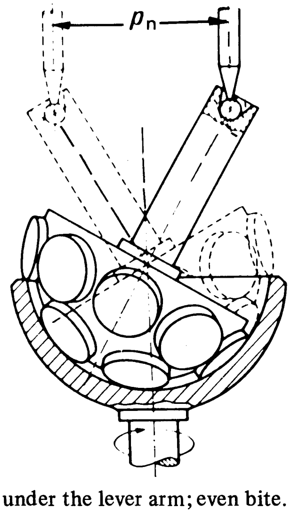


Figure 1.60 Block holder under the lever arm; even bite. p_n Normal path of the pin

When the block is on top and the movement of the ball pin is restricted to only one side of the spindle centre, then the wear shifts predominantly to the centre of the block (figure 1.61). In this case the block holder remains in such a position that its edges rotate much more on that part of the grinding shell where its linear speed is a minimum, and so it produces the minimum grinding force at the edge of the block.

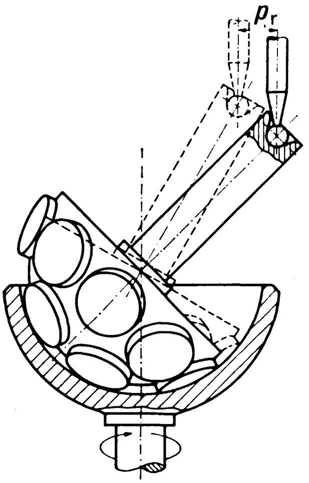


Figure 1.61 Block holder under the lever arm; excessive central wear. p_r Restricted path of the pin

These considerations also hold good and are particularly important for flat surfaces. Here also the job holder can be driven by the spindle or else guided by the ball pin, but the former practice is generally preferred. In the case of the grinding of flat surfaces, the wearing ratios are more obvious. The surface of the job is evenly worn when the ball pin swings equally on both sides of the machine spindle (figure 1.62). By restricting the movement of the ball pin to the central zone, it will be seen that the central zone of the block wears more. On the other hand, by restricting the movement of the ball pin to one side of the block, the edge of the block is worn more (figures 1.63 and 1.64).

Turning and milling of spherical shells

While describing the process of grinding we have observed the importance of maintaining the precise radius at each stage. Since the tool castings are to be machined to high accuracies, an important question arises as to how long radii tools can be rationally and accurately achieved when one does not have a lathe with a correspondingly long bed-length. The general tolerance on radii in optics is

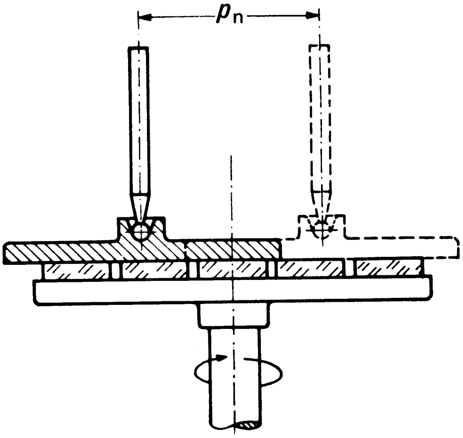


Figure 1.62 Flat block holder on the spindle with the flat tool under the lever arm; even wear. p_n Normal path of the pin

one per mil, that is, for a radius of 1000 mm, the deviation permissible is approximately 1 mm.

For radii below 200 mm, one can work to closer tolerances, because the optical measuring equipment available for test plates can give readings to 0.001 mm. For the turning of radii up to 1000 mm, the commercially available direct radius turning lathes are quite suitable and these can be set with the help of slip gauges.

With the special lathe tool post arrangement shown in figure 1.65, spherical surfaces may be turned with radii from 200 mm to infinity. The turning tool post is driven across the lathe by a normal cross-slide carriage, but the longitudinal tool

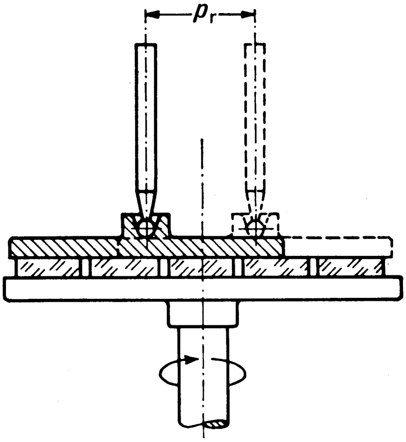


Figure 1.63 Flat block holder on the spindle with the flat tool under the lever arm; excessive central wear. p_r Restricted path of the pin

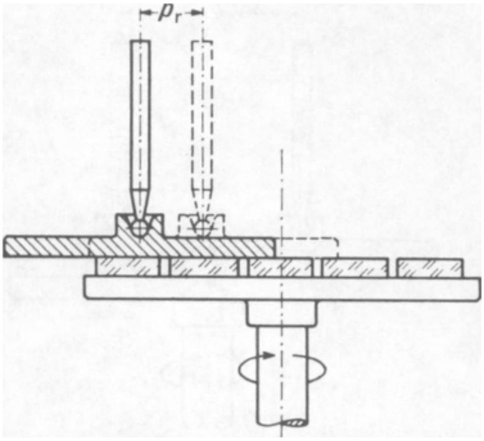
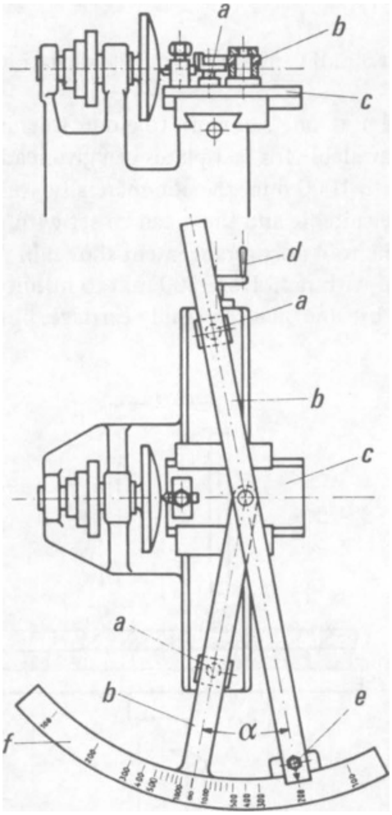


Figure 1.64 Flat block holder on the spindle with the flat tool under the lever arm; excessive edge wear. p_r Restricted path of the pin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300
400
500
1000
∞
1000
500
400
300
200
100

Figure 1.65 Radius turning lathe for radii from 200 mm to infinity. *a* Scale pivot points, *b* sliding bars, *c* longitudinal slide actuated by the sliding bars, *d* cross-slide of the tool post, *e* clamping screw for adjustment of the radius angle, *f* radius scale; α radius angle

position is controlled by two sliding bars which are set at an angle to each other to generate the required circular locus. This locus is transmitted to the tool post through a fixed pivot on the tool carriage *c*, as the bars slide through two pivoting bearings *a*.

For very long radii, where high accuracy is required, it is possible to cut precise templates to control the lathe cross-slide, but there is a sounder and more generally useful method for cutting spherical metal tools of all radii based on the single point fly-milling principle. This method is illustrated in figure 1.66, where it is clear that to generate a spherical tool of a particular radius R, the head angle θ must be chosen in accordance with the following equation:

$$\theta = \sin^{-1} \frac{r}{R}$$

The principle involved in this cutting action is that any sectional cut of a sphere of radius R must be a circle of some radius between zero and R, and thus, as long as R is longer than r, the circular path of the cutting tool tip may be made to coincide with the required sphere by choosing θ appropriately. The sphere is

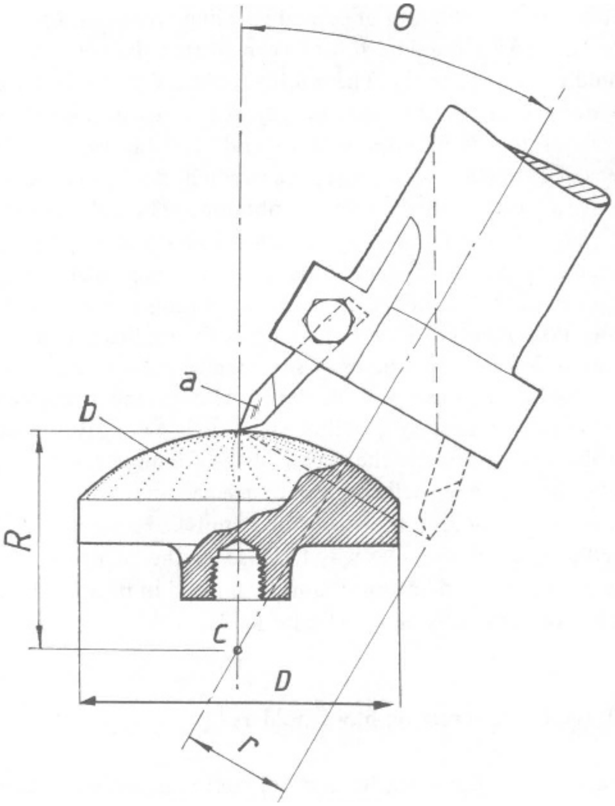


Figure 1.66 Fly-milling of spheres. *a* Cutting tool, *b* surface being cut, *c* centre of curvature

generated by rotating the work about a centre line that passes through the tool tip locus. Obviously, the maximum diameter of tool $D_{\max}$ that may be cut with a cutter of radius r is given by

$$D_{\max} = 4r\cos\theta$$

A further technique for cutting spherical tools is to use a modern numerically controlled lathe, and merely feed the coordinates of the circular curve to the tool post.

Smooth grinding with diamond tools

Particularly in the case of what an optician calls a 'shallow' curve, that is, a curve where the radius is much longer than the diameter of the lens or block holder, one can replace the grinding process by grinding with the help of diamond tools. With fine grain diamond grinding tools, the glass surfaces can be worked individually or in block holders, so that these can be polished straight away without any further grinding with loose abrasives. The advantage of this method, which may be semi-automated, lies in the elimination of several grinding processes, the saving of grinding materials and a reduction in tool wear, so that the continual correction of the tools should not be necessary. The milling tools are charged with diamond particles and are used in exactly the same way as the cast iron grinding tools on lever-arm machines, but with a supply of mineral oil rather than water and higher rotation speeds. The diamond grain size, the running speed, and the loading should be adjusted until a cleanly milled surface is obtained. The diamond grinding tool must, for the purpose of obtaining interference accuracy at the polishing stage, possess the necessary radius accuracy. This radius accuracy is about ±0.0008 mm and to achieve this in the manufacture of diamond tools is not easy, because even by moulding against an accurate tool of the opposite radius, the facing on the tool distorts because of heat in the process of sintering. A radius correction of the diamond-faced tool is of course possible, but time-consuming, and can be conducted by an optician only with lengthy grinding with a coarse abrasive on an accurate cast iron tool. If this is to be done by the maker of the diamond tool himself, then he must also make the opposite shell to interference accuracy.

For this reason the diamond tools for fine grinding are made with diamond pellets blocked together in a similar way to lenses in the pellet-sticking method: the pieces are arranged on an accurate tool, then fixed in position by brazing or with some adhesive such as 'Araldite' (figure 1.67).

Operation 10: Polishing lenses on block holders

The smoothed lenses on the block holders are next polished so that the glass surfaces become transparent. For this purpose, polishing rouge and water are applied

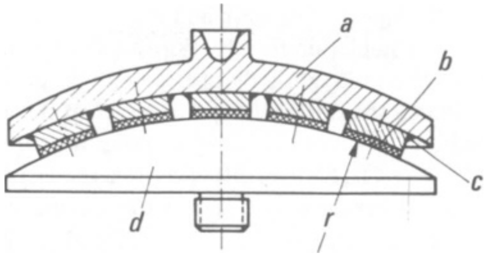


Figure 1.67 Diamond grinding shell. *a* Grinding shell, *b* diamond-charged grinding pellets, *c* welding or adhesive material, *d* opposite curvature tool, *r* required radius

between the glass and the oscillating pitch polisher. The polisher is a pitch layer stuck in a cast iron shell (figure 1.68). The polishing operation is mostly carried out on the lever-arm type of machines which are similar or identical to those used in grinding and smoothing. For the purpose of polishing, the rules of lever-arm adjustment to obtain edge or central wear and for normal movements are the same as those for grinding. Also, the effects of shell correction on the interference figures are the same as in the case of grinding.

The block holders are cleaned of any remaining abrasive dust with moderately warm water, and then attached to the spindles of the lever-arm machines. Before the polishing shells are put on to the individual block holders, these must be made to adopt the surface radius of the lenses, so that a uniform polishing action can begin straight away on the whole of the block surface. For this purpose a pot of hand-warm water is kept ready near the polishing machine, so that, by a short immersion of the polishing shell into it, the pitch softens. On putting the polishing shell with a little smeared polishing rouge on to the block holder, the pitch is soon able to adapt itself fully to the smoothed lens block surface form.

The polishing worker is concerned that his block is given the correct radius and shape (according to the test plate) in the shortest possible time and also that the surface is fully polished. To this end he must verify how the grinding worker has

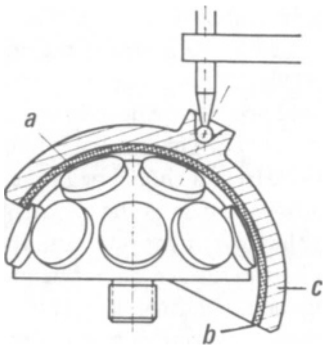


Figure 1.68 Polishing shell under the lever arm and the block holder mounted on the spindle. *a* Polishing material, *b* polishing pitch, *c* cast iron shell

delivered the block, with respect to its form and texture, and further, whether the polisher is biting the block holder uniformly. For this verification, the worker removes the polisher after polishing for about five minutes, puts the test plate on the work and also examines the difference in the degree of polish between the edges and the centre of the block to determine how the polishing shell is biting the glass. Depending on what he observes, he then either returns the incorrectly smoothed block to the smoothing worker, or he tries another immersion of the polisher in the warm water to achieve a better polishing action. Usually, when the block holder is found to have been properly smoothed, it is mated again with the polisher and polished further with the addition of more rouge. The polishing rouge should always be applied sparingly, because too thick a layer results in slipping rather than polishing. According to the type of polishing method, that is, whether the polishing rouge is applied by hand or by automatic supply, the optician decides on the quantity of polishing material that he has to add. The correct rate of feed and the consistency of the polishing material is soon understood by the optician from the appearance and the surface quality of the polished glass surface.

Polishing does not have any influence as far as the maintenance of lens thickness is concerned, because in the course of normal polishing, even in extreme cases, only 0.03 mm of glass would be removed. This reduction in thickness should be taken into consideration when calculating the design of the block holders for lenses that have to be made to particularly tight thickness tolerances, otherwise one must work with witness marks for accurate thickness control (see operation 9).

After polishing for some time, the craftsman lifts the polisher again, so that by taking guidance from the test plate reading he can adjust the bite of the polisher with a view to achieving the required surface radius within the permissible interference band tolerance. The last adjustment is usually done by correcting the polisher and, since the polishing machine has the same action as the grinding and smoothing machine, the correction of polishing shells is done in the same way as has already been explained for the correction of grinding shells. In the case of polishing, however, the polishing shell must be scraped and/or notched. When a test plate is put on a convex or concave surface and it shows contact at the edge, similar to that observed when dealing with the correction of grinding shells, then some pitch must be removed from the centre of the polisher so that the polisher will bite more at the edge. This relieving is done by scraping a spiral in the middle of the polisher; the spiral should begin quite deep in the centre and should become gradually shallower at its outer end. This cutting is done by hand with the help of a knife, as shown in figure 1.69. Here it should be borne in mind that a hole, 15 mm or so in diameter, should always remain in the centre of the polisher, so that there is always enough space for the flow of the pitch and the rouge. If there is no such hole in the pitch, then a spherical surface cannot be produced on the glass, because the dammed-up pitch brings about an irregularity on the centre of the surface.

Similarly, if the test plate shows contact in the centre, then a spiral groove needs to be cut at the edge of the polisher. This groove should tend to be deeper as it extends towards the edge, as shown in figure 1.70.

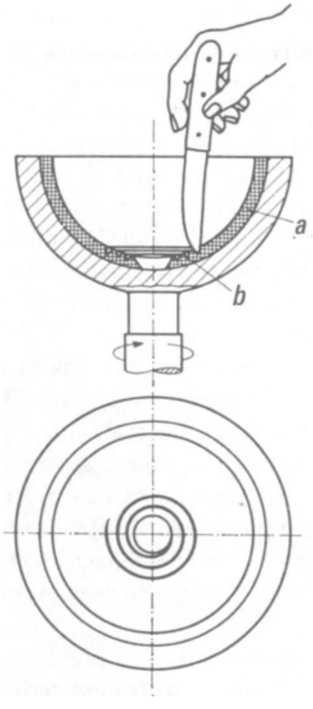


Figure 1.69 Central correction of pitch shell. *a* Polishing pitch layer, *b* groove

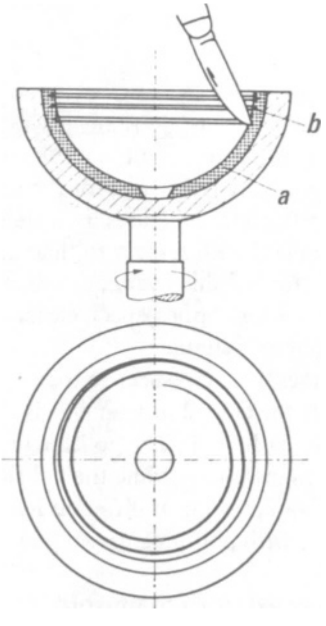


Figure 1.70 Edge correction of pitch shell. *a* Polishing pitch layer, *b* groove

Along with this careful control of the polisher, the craftsman also has to watch the progress of the surface quality right up to the end of the running time. During the last phase of polishing it is usual to have very little polishing rouge mixed with the water; finally only water is used because there will still be enough polishing rouge particles on the surface of the pitch to give a good polish, without leaving a messy surplus of rouge to be cleaned off at the end, which might stain the surface.

The typical velvety brown layer which indicates the firmly settled rouge particles on the outer surface of the pitch is called a polishing crust. This crust will form easily if the pitch is suitable, and the craftsman judges from its appearance whether the polishing work is proceeding well or not and how the pitch suits the glass type that is being worked.

After the completion of the polishing time, the quality of the polish is examined with a X6 magnifier and a clear 60 watt lamp. The polishing worker must know the details of the appearance defects that can be allowed in accordance with the appropriate quality specification, otherwise he may spend far too long on lenses that need not be of very high cosmetic quality or let significant defects pass that will not be acceptable in the finished lens. After finishing the polishing the block holder is unscrewed from the machine, sponged under moderately warm water and dried. Complete drying is essential to avoid water marks and stains on the surface of the glasses.

The finished blocks are examined again in the polishing inspection department and the polished lens surfaces are covered with a protective lacquer, so as to save them from getting dirty in the course of deblocking and reblocking for the working of the second side.

The polishing process

What actually happens during the course of polishing glass is not fully understood; however, the important things that matter, and the results of the optician's experience based on his hand work, are given here for the use of the practical man.

The optician must polish the fine ground lenses individually or on block holders until he achieves a specified standard with respect to their appearance and surface accuracy. The process materials for polishing vary according to the requirements of the optics; for example, illuminations optics, spectacle lenses and high-performance optical components all use different techniques.

In view of the strict requirements with respect to their surface accuracy, the polishing of optical components for optical instruments is achieved with polishing rouge and water working jointly with pitch. The polishing rouge is usually cerium oxide and is readily available commercially, while the polishing pitch is made up of specific mixtures of coal tar and pine tar of different hardnesses and different types of wax and rosin, together with polishing rouge, prepared and used in accordance with experience.

Pitch polishing work is conducted either 'warm' or 'cold'. Under the category of warm polishing comes the traditional method, in which the water and polishing rouge between the pitch and the glass is evaporated, so ultimately leading to dry polishing. In this process the polishing worker endeavours to maintain the state of dry polishing as long as possible and he must therefore add only a small quantity of rouge and water so that the warmth between the glass and the pitch can evaporate it. In this warm process the glass obviously becomes warm, owing to friction, and particularly when it is applied to lenses on hard block holders, the cement with which the lenses are stuck on the block holder cannot necessarily compensate the expansion difference between the glass and the iron. Thus, when the heat that is generated makes the cement softer and the smearing of cold water contracts it unequally, this creates cement strain and consequently surface shape errors on the lens. On account of these many variable effects in warm polishing, it will be appreciated that craftsman can only control a limited number of polishing spindles – at the most, say, twelve; since also the polishing rouge is applied by hand, this also has to be done with careful attention, coupled with skill and experience, and thus well-trained optical craftsmen have to be employed for this work.

The cold polishing process is quite different. The rouge and water is supplied automatically in a continuous stream and, although the polishing time is longer, owing to the reduced friction between the polisher and the lenses, the thermal environment on the block is constant and may be controlled by the thermostatic heating of the slurry, so leaving the polishing craftsman free to control up to as many as 36 spindles. This can dramatically reduce the polishing costs and also allow the employment of assistant workers to multiply the productivity of the senior craftsmen.

For the purpose of cold polishing, the blocks are mounted on spindles with rotating bowls. A mixture of polishing rouge and water is kept in the bowls and, owing to centrifugal force, this mixture is hurled on to the bowl walls, and from there it is conducted via a flexible scoop on to the block being polished (figure 1.71).

This method of automatic polishing rouge supply justifies itself most of all in the case of mass production, where it compensates for the expenses of supervision in the grinding shop and for the maintenance of the high accuracies in radii for truing and fine grinding which are necessary to suit the specified edge bite required by the polisher at the start of polishing. In the case of polishing on lever-arm machines adjusted for normal movements, almost no polishing shell correction should be necessary.

The hole in the central zone of the pitch shell must also be cut, in this case, to accommodate the flow of the pitch, although the lower temperature of the process and the possibility of using harder pitch reduces the need to watch this. In the case of machines with stationary bowls, the polishing material can be fed automatically by a pump. An electric pump below the machine can bring the polishing material on to the block holder. From there it goes into the bowl, and finally runs back to the storage tank (figure 1.72). One pump can supply several machines.

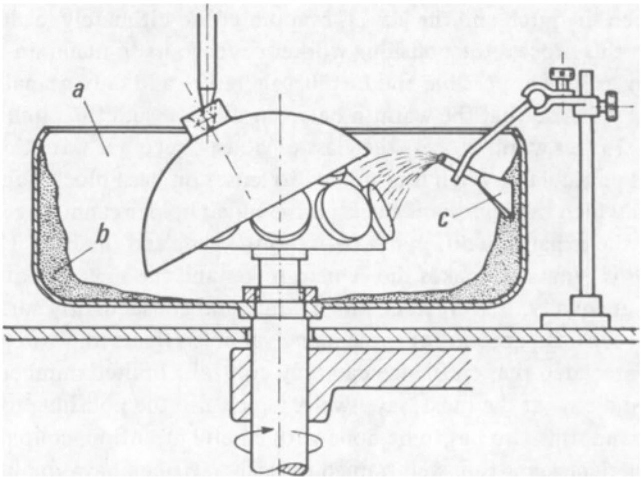


Figure 1.71 Automatic polishing material supply with a rotating bowl. *a* Rotating polishing material bowl, *b* polishing material, *c* channel built as a sprinkling tube

For both the methods, that is, for both warm polishing as well as for cold polishing, one has to make some preparations and establish certain conditions which are necessary for the polishing work.

An important condition is the temperature of the workshop. It has a direct relationship with the progress of the polishing process, because of the necessary evaporation heat and the dependence of the hardness of the polishing pitch on temperature. Also the humidity of the air in the polishing room has an influence on the rate of evaporation and therefore of cooling. Although pitch is continuously liquid at all temperatures it is possible to identify practical temperature-dependent

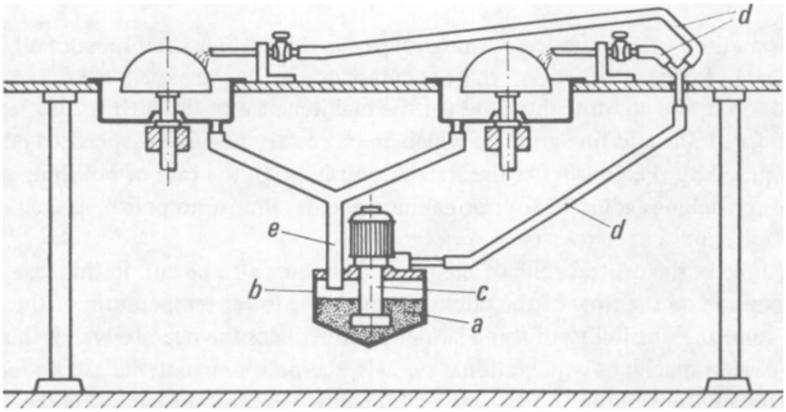


Figure 1.72 Automatic polishing slurry supply with a stationary bowl. *a* Polishing slurry, *b* storage tank of polishing slurry, *c* pump for polishing slurry, *d* supply line for polishing slurry, *e* drain for polishing slurry

turning points in its properties; thus the workshop temperature, the solidification point of the pitch and the point of its plastic deformation should all lie close to each other. At the workshop temperature, the pitch must stay hard and brittle, the solidification point must be close, at 2–3°C above the room temperature, and the beginning of the plastic deformability may lie at the most 5–8°C above the solidification point, so that the block holders with the lenses do not need much warming before polishing. In this way it should be clear how essential it is to determine the exact hardness of the pitch. There is also the influence of the external temperature and the optician should, if necessary, make pitch mixtures of different hardness to suit summer and winter conditions. To avoid dependence on outer temperature, one can regulate the air in the polishing room through air-conditioning. This also maintains the block holders, the optically contacted blocks (which are very sensitive to temperature changes) and the test plates at a uniform temperature.

This temperature control also helps to avoid the formation of stains and blemishes in the case of sensitive glasses, or 'pitch tinge' which is seen as a brown layer that forms on nearly finished polished glass surfaces at a certain temperature, and which can only be removed by further polishing. When this brown layer is frequently formed, the craftsman may put a little common vinegar in the polishing rouge, although this can cause problems with some glasses and should only be done in consultation with the workshop technologist.

A further part of the work preparation for the optician is the making of the polisher. The cast iron shells that are to be used for the purpose are cut by the machinist so that the radius of a polishing shell meant for the polishing of convex blocks is greater by 3–3.5 mm, and that meant for polishing concave blocks smaller by 3–3.5 mm than the polishing radius. The polishing shell is screwed on to a spindle, and a predetermined quantity of hot, fluid polishing pitch is poured into it. Next, a pitch pressing tool which has been cut to the exact polishing radius is smeared with liquid soap or polishing slurry and pressed into the pitch lying in the shell (this pitch pressing tool is usually the mate of the smooth grinding tool that is being used). The machine spindle is set in rotation and, by hand pressure, the still-fluid pitch is uniformly distributed in the shell, up to the edges (figure 1.73).

It must be carefully ensured that the thickness of the pitch layer is uniform over all the surface, otherwise it will produce an irregular surface on the lenses. This can be particularly difficult for blocks that subtend a large angular aperture, and it is probably worth weighing out the correct volume of pitch or using three steel balls of the appropriate diameter to achieve the required polisher thickness. As already explained, it is essential that the polishing system and the glass suit each other. Certain glass types have the property of not allowing the polishing rouge and pitch to achieve a good polishing effect and the optician comes to know from experience if a polishing crust is not developing on the pitch surface, in which case he can take appropriate corrective action by changing the composition of the pitch, or perhaps changing the polishing compound.

The polishing rouge is, if necessary, put through an ageing process. The rouge

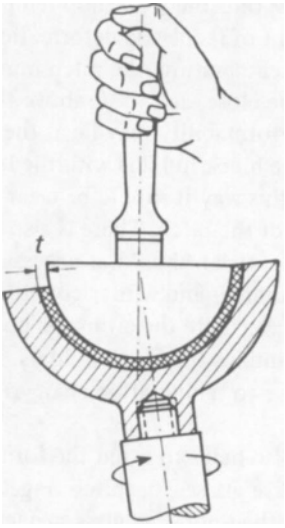


Figure 1.73 Formation of a polisher. *t* Pitch layer thickness approximately 3.5 mm

received from the manufacturer is mixed with water, boiled and stirred. The slurry formed should loosen burnt and clumped rouge particles from each other. After cooling the rouge is once again filtered through a fine sieve to separate the coarse dirt and then stored in carefully covered wide-necked flasks for a long period – if possible for several weeks. During this period that part of the contents that is disadvantageous to the polishing process is separated and comes to the top of the water, and so may be skimmed off.

No interference accuracy is required from the polished surface of condenser lenses; one can therefore use a felt lining instead of a pitch layer in the polishing shell that is used for them. With the use of felt, the polishing time required is less.

Operation 11: Unblocking lenses from pelleted block holders

The lenses are unblocked as a result of contraction through the effect of cooling. After finishing, the block holders are put in a refrigerator, and cooled to below 0°C. In this way the iron, the pitch and the glass contract to a different extent and in this way the lenses become detached. The lenses are then picked up and laid in transport trays or in cleaning containers.

Mostly the pellets also get detached from the block holders and they are collected and melted together for making new pellets for further work.

In the case of long radius blocks, one can sometimes unblock the components by hammering on the rear side of the block. To prevent damage to the lenses in this case, a thick cloth is, of course, laid next to the glass components.

Operation 12: Cleaning the lenses

After the second lens side is polished, unblocked and brought to room temperature the lenses are laid in a spirit-filled container. The spirit dissolves all the remnants of cement, pitch and lacquer.

After an appropriate period of time the lenses are taken out of the spirit and dried with a clean cloth. In case any thick pitch remnants are not yet fully dissolved, this cleaning process can be accelerated by rubbing them in spirit with a hogshair brush or a chisel-ended dowel. The cleaning work is not difficult but requires care and attention.

The automatic cleaning of optical components using ultrasonic cleaning methods

With ultrasonic cleaning methods the cleaning of optical components can be automated. However, the specific arrangement of ultrasonic chambers for each type of cleaning has to be determined by trial. Finished polished optical components are cleaned in this way by suspending them in suitable frames which are immersed in different solvents in sequence, such as methylated spirit, perchlorethylene, detergent, calcium solvent and, finally, wetting agent. The linking of the individual chambers with a transport line makes the installation automatic.

In the cleaning of optical components, the final droplets of solvent left at the end of cleaning must be thoroughly removed so that they do not leave behind drying marks and for this reason, after carrying the components through the different cleaning baths, the automatic transport line must also carry them through a vapour-drying chamber. In the case of a well-designed and tuned cleaning chain, the components can be directly aluminised, silvered or antireflection coated without any hand cleaning at all.

Operation 13: Centration of lenses

It is essential in optical instruments that, to the highest achievable accuracy, the axis of the outer cylindrical edge of the lens must coincide with its optical axis (which is defined at the line joining the centres of curvatures of both the surfaces of the lens) (figure 1.74). In this operation, the longer the radii of the surfaces, the greater is the difficulty in centring the lens.

The tolerance for the allowable displacement of the optical axis from the axis of the outer edge of the lens should be given on the component drawing in accordance with appropriate drawing standards. An account of the extra allowance to be given on mouldings has already been given in the 'sizing table', but in the case of particularly long radii the extra allowance for centring and edging must be determined separately for each case.

In the case of a well-centred lens of course, when it is cemented to the edge

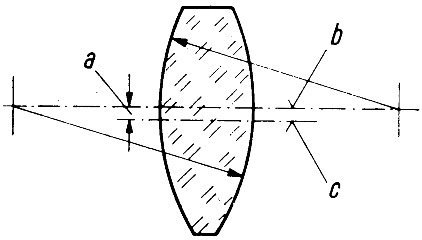


Figure 1.74 Lens decentration. *a* Axial displacement centring error, *b* optical axis, *c* axis of the outer edge

of a rotating tube chuck so that both its optical surfaces rotate about their own optical axis, then the cylindrical edge of the lens should also rotate about its own centre line.

Centration by the observation of reflected images

The images of bright objects picked up by the eye after reflection from the lens surfaces rotating about their optical axis must remain stationary. In the case of the decentred positioning of a lens on the rotating mandrel, the reflected images will oscillate. The lens that is to be centred is stuck on the datum edge of the mandrel with a hard, low-melting-point wax. The mandrel has a datum edge that has been turned to rotate truly with the bearing spindle (figure 1.75). The mandrel is heated with a small gas flame until it reaches the stage at which the centring cement just melts, while the lens is also warmed on an electric hot plate and then pressed on to the mandrel rim so that it rotates with it. A higher accuracy in

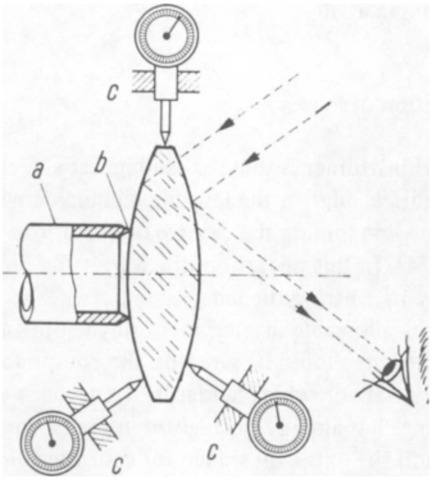


Figure 1.75 Centring by observation of reflected images. *a* Cementing mandrel built as a tube, *b* datum edge, *c* dial indicators positioned for examination

centring is more easily achieved when the deeper curved side is cemented to the mandrel. When the mandrel is still hot, the centring spindle is rotated by hand, or with a regulated motor actuated by a foot lever. Through a hand-held wooden peg-tool supported on a post, the lens is then pushed and manipulated against the rim of the mandrel until the images reflected from both lens surfaces appear stationary. When this condition is achieved then the mandrel is cooled with a sponge, and the centring spindle is transferred to the edging machine (figure 1.76).

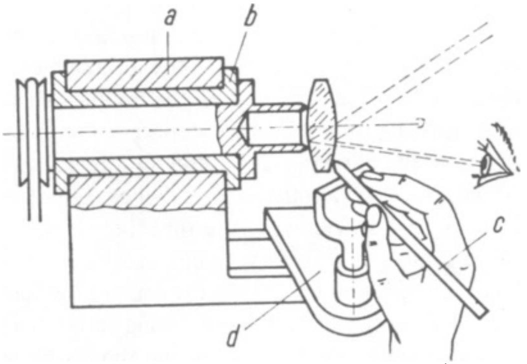


Figure 1.76 Centring with a wooden peg. *a* Split bearing the exchange spindle, *b* exchange spindle with the mandrel for cementing, *c* wooden peg, *d* supporting post

This method for the centring of lenses by the unaided observation of reflected images is not dependent for accuracy on the diameter of the lenses, and when conducted in a conscientious way gives sufficiently high accuracy in the case of the surface radii generally involved in photographic lenses.

The certainty with which the centring work can be done is, however, limited by the eyesight, judgement and state of fatigue of the individual who centres the component and decides whether the reflected images are stationary or not. To increase the sensitivity of this process a magnifier may be put in front of the observer's eye or, in order to assess the extent of wandering of reflected images within a quantitative tolerance zone, a compound optical system with a reference graticule that can measure the extent of movement of the reflected images can be used.

Optical centration with transmitted light

Lenses can alternatively be checked for their centring errors with transmitted light. The lens is cemented to a mandrel that has a hollow bore and this combination is carried over to an exact replica bearing on the viewing instrument and thus brought into an aligned optical path. Every change in direction occurring because of the non-centred positioning of the lens on the mandrel will then show itself. The optical centring apparatus consists of a collimator with a graticule on which a simple cross-line is marked, a telescope with a double cross-line graticule mounted on the same centre line and a coaxial conical bearing.

In terms of the ray deviations introduced by a specific surface tilt, transmitted light centring is less sensitive than reflected light centring by a factor of approximately four, but this lack of sensitivity may be compensated by using a longer optical lever path with a laser light source, and in any case the transmitted light method is closer to the situation that the lens is used in, so that unnecessary precision, with its attendant costs, can be avoided.

The lenses are warmed on a hot plate and the mandrel is heated until the cement can be applied, then the warmed lens is mounted on it and adjusted by hand so that the collimator cross-line is imaged between the double cross-line graticule of the observation telescope. The spacing between the double cross-lines should be equal to the specified centring tolerance. By rotation of the mandrel, it can be checked whether the imaged collimator cross shows more or less movement than that allowed by the tolerance. Simultaneously, a dial gauge may be run in contact with the underside of the lens surface to verify that there is no decentration there. When there is no more optical or dial gauge indications of centring errors, the mandrel is cooled with compressed air so that the cement hardens. Depending on the focal length of the lens to be centred, the centring apparatus should be adjustable so that the viewing height for the eye and the instrumental sensitivity can be maintained at fixed values. For this purpose, a folded optical path is provided and, to reach different image points, auxiliary lenses may also be introduced (figure 1.77).

Optical centration by autocollimation

This method can also be applied in the finishing of photographic lenses (figure 1.78). The operations are similar to those used in the case of centring with transmitted light. In this case one curved surface lies on a true tube chuck and the lens is centred with the help of only the top surface. This has the advantage that, for centring lenses of different focal lengths, one does not need any interchangeable auxiliary lenses, because the autocollimation imaging by the top surface of the lens is brought to a constant position simply by shifting the prism system. It is advisable not to use this type of centring for short radius lenses, because these do not give easily recognisable autocollimation images.

The edging of lenses

After optical centration, lenses are edged to the desired diameter on the edging machine. By the use of a suitable mount for the spindle (in the case of centring by the reflection method) or for the hollow mandrel (in the case of optical centring by transmission), the centring accuracy is exactly maintained on the

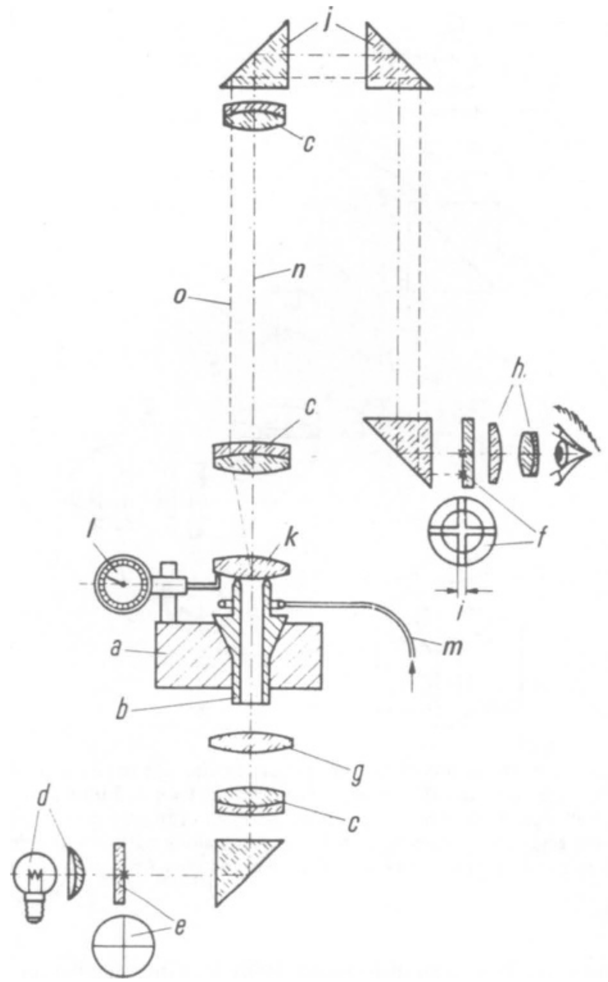


Figure 1.77 Principle of an optical centring apparatus utilising transmitted light. *a* Bearing for the mandrel, *b* mandrel with a sharp edge rim and conical bearing, *c* optical system consisting of a number of achromats for imaging the collimator cross-line on to the ocular graticule, *d* illumination system for the collimator graticule, *e* collimator graticule, *f* ocular graticule, *g* interchangeable intermediate lens, for neutralising the test lens focal power, *h* ocular, *i* tolerance cross and tolerance circle on the ocular graticule, *j* adjustable prisms system, *k* lens to be centred, *l* dial indicator for testing the centration of the datum surface, *m* compressed air channel for cooling of lens cement, *n* ray path for a centred lens, *o* ray path for an eccentric lens

edging machine (figure 1.79). The edging machines are, in principle, the normal cylindrical grinding machines in which the main feature is the interchangeability of the centring spindle. The diamond tool is brought against the lens edge with the help of a swivelling arm or a slide and must be further moved either by a

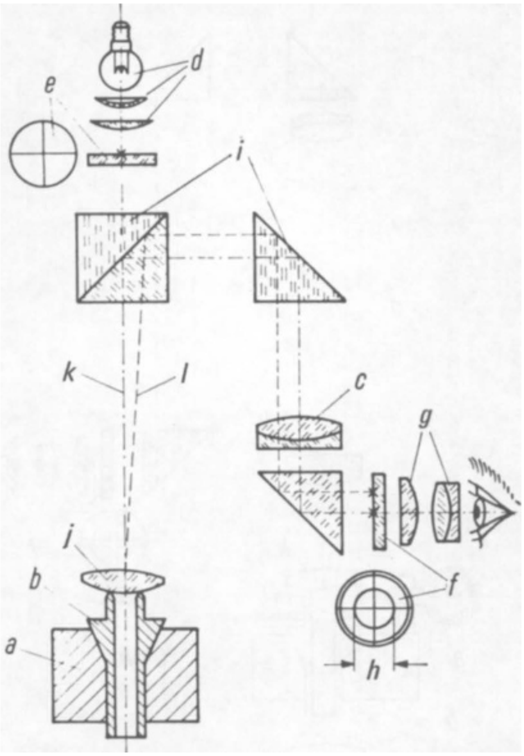


Figure 1.78 Principle of the autocollimation optical centring apparatus. *a* Mandrel bearing, *b* mandrel with ring edge and conical bearing, *c* viewing objective, *d* illumination system for the graticule, *e* collimator graticule, *f* ocular graticule, *g* ocular, *h* reference cross and tolerance circle on the ocular graticule, *i* prism system displaceable along with the illumination arrangement, *j* lens to be centred, *k* ray path for a centred lens, *l* ray path for an eccentric lens

screw driven by a handwheel or automatically by location against a curved cam until the finished diameter for which it has been adjusted is reached. After edging the diameter is checked, usually with a ring gauge.

Accuracy obtainable with optical centration methods

Figure 1.80 shows an approximate curve of the accuracy that can be achieved in centring. It gives an average value for the three optical centring methods: using reflection, using transmitted light, and centring with the help of autocollimation. The shape of this curve is based on theoretical centring forces, but the magnitudes are based on practical experience in the workshop. The accuracy achieved in centring by optical means is dependent on the optical effect of the lens, that is, the optical power resulting from the curvature relationship of the two sides of the lens to one another. This is given by the value of $(1/r_1 + 1/r_2)$, as in the theoretical

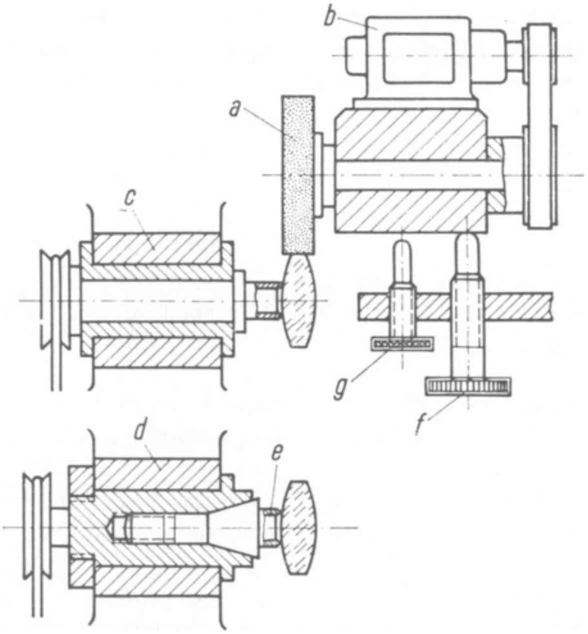


Figure 1.79 Edging machine arrangement. *a* Diamond milling wheel, *b* motor drive, *c* clampable exchange bearing, with an interchangeable spindle and mandrel for centration, *d* centration instrument bearing, *e* mandrel with a conical bearing and datum ring edge, *f* feed screw, *g* stop screw

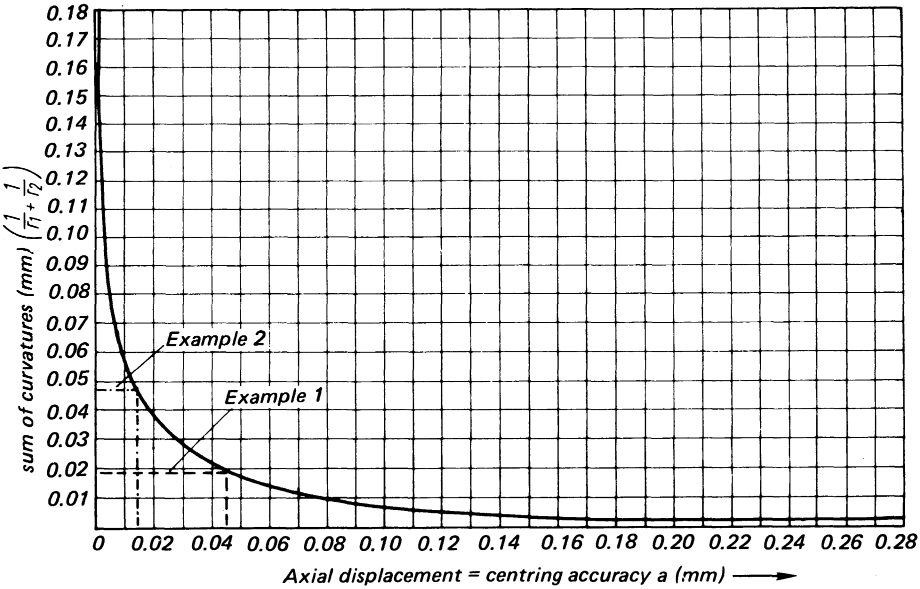


Figure 1.80 Centring accuracy that can be achieved by optical methods (including the reflection method) depending on the sum of lens surface curvatures ($1/r_1 + 1/r_2$), concave radii having a negative sign

lens power formula, where concave radii are taken to have a negative sign. The sum of the curvatures can be calculated for any specific lens and its potential production centring accuracy can be read directly from figure 1.80, or calculated from the equation

$$\text{potential centring accuracy } a = \frac{0.0007}{\left(\frac{1}{r_1} + \frac{1}{r_2}\right)} \text{ mm}$$

(see figure 1.74 for the interpretation of a).

For the two examples shown in figure 1.80 the application of the total curvature is as follows:

A concave–convex lens with radii +30 mm and –70 mm gives a total curvature value of 0.0333 – 0.0143 = 0.019 and therefore a centring accuracy of 0.045 mm.

A biconvex lens with radii + 30 mm and +70 mm gives the curvature value of 0.0333 + 0.0143 = 0.0476 and therefore a centring accuracy of 0.015 mm.

This approximate method for the determination of centring accuracy is of assistance in the production engineering office for planning and estimating, and to the shop foreman for establishing the accuracy that should be demanded.

Mechanical centration with the bell-clamping method

Lenses with deeply curved radii can also be centred mechanically and simultaneously held sufficiently firmly to enable them to resist the transverse pressure of the diamond wheel that mills the lens edge. By mechanically centring and such holding of the lens, the operation of centring and the time required for transferring the spindle from the centring bench to the edging machine is saved. In the case of centring by mechanical methods the lenses are clamped by spring pressure between the edges of two coaxial, synchronously rotating steel bells. In this position, the diamond tool mills off the run-out of the lens and reduces it to the required diameter (figure 1.81).

The centring effect is obtained, of course, on the same principle as sliding on an inclined plane, when the optical axis of the lens does not lie on the mechanical axis of both the clamping bells, and then there is a wedge effect that slides the lens to its centred position (figure 1.82).

This centration is potentially more reliable if the lens surface radii are short and the lens is of large diameter and, for this reason, the diameters of the clamping bells are chosen as large as possible, so that the edges of the bells are located near the periphery of the lens that will ultimately be covered by the mounting of the lens, thus minimising the effect of cosmetic blemishes introduced by the edging. With the largest possible diameter of the clamping bells, the angle between the

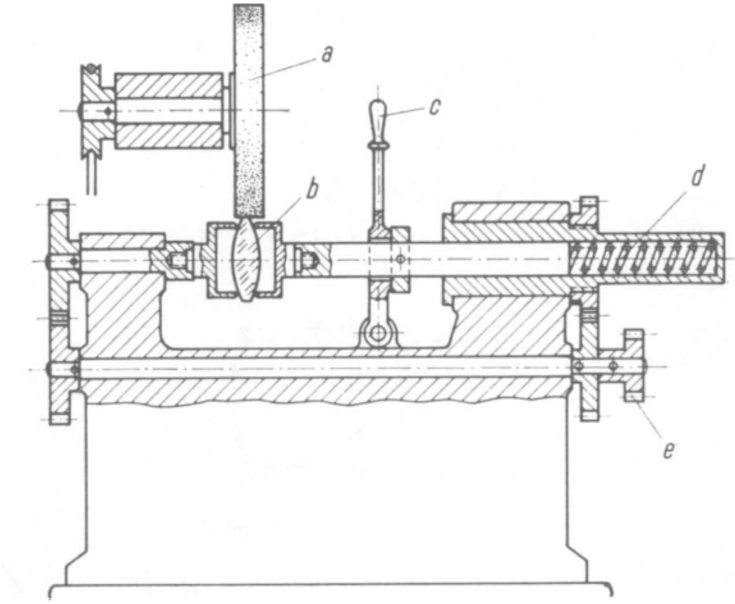


Figure 1.81 Scheme of centring machine by bell clamping. *a* Diamond tool, *b* clamped lens, *c* clamping and unclamping lever, *d* clamping spring, *e* drive for rotation of the bells

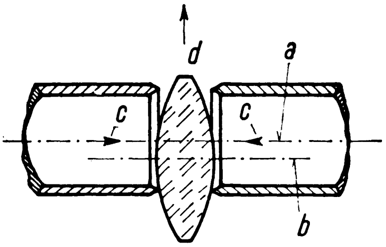


Figure 1.82 Lens lying eccentrically between the clamping bells showing the influence of the centring effect. *a* Axis of clamping bells, *b* optical axis of the lens, *c* pressure direction of the clamping bells, *d* thrust direction of the lens

tangents at the contact points of the lens surfaces with the bells is also maximised, so that as a consequence the centring force is a maximum (figure 1.83).

The sliding friction between the polished steel and the glass is dependent on the lubricating material used. It has been observed by experience that, with the mineral oil normally used for the purpose, lenses whose curvature tangents form an angle of 8° with the contact points of the bells still slide and centre without any special encouragement (figure 1.84). In certain circumstances, difficulties can arise even when the angle between the tangents is as high as 8.5°. When difficulty is experienced careful adjustment of the clamping force is necessary, but in any case the force should be sufficiently large that the clamped lens can withstand

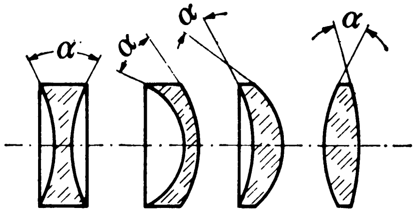


Figure 1.83 Tangent angle equals sliding angle in the case of different types of lens. α Tangent angles

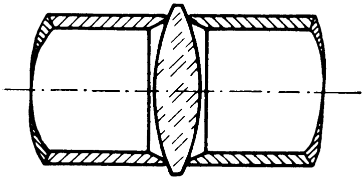


Figure 1.84 Lens centred between the clamping bells

the milling pressure. In the case of horizontal clamping, the weight of the lens itself can adversely affect the centration and put the centring accuracy in doubt. Therefore, for lenses of larger weight, it is better to use vertical clamping, so that the gravitational axis lies along the longitudinal axis of the clamping bells. The vertical clamping method also allows itself to be combined with the autocollimation centring method and, with this, lenses with a curvature tangent angle below 8° can still be edged (figure 1.85). However, the lenses in this case do not shift by themselves, but must be moved by hand until the cross-lines coincide, and only then can the full clamping force be applied.

The application of bell clamping is not limited to the milling of lens edges. The rounding of the profile of Porro prisms may also, for example, be achieved, so that these lie symmetrically between the parallel ground faces of the prism, to avoid adjustment difficulties arising at the time of assembly. The most economic milling of these features can be done on a machine where the diamond wheel spindle also holds a plane cylindrical roller of equal diameter for limiting the feed against a template on the work spindle. The prism is laid in a prismatic holder and positioned by a clamping bell (figure 1.86).

Centring accuracy in the bell-clamping method

As in the case of optical centration, so in the case of bell clamping the centring accuracy can be given in quantitative terms. It is dependent on the sliding angle α, which is formed by the tangents on both sides of the lens at the clamping diameter (figure 1.87). The limiting value of the sliding angle at which the lens can centre itself without additional help can be calculated from the coefficient

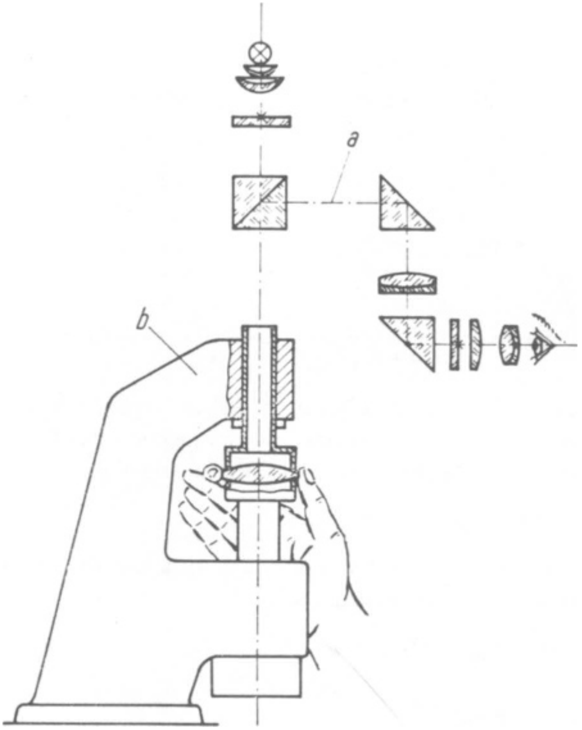


Figure 1.85 Optical ray path for centring by bell clamping combined with optical alignment by autocollimation. *a* Scheme of optical ray path (see figure 1.78), *b* vertically placed clamping/centring machine

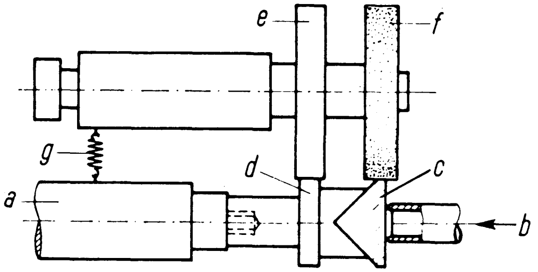


Figure 1.86 Edge milling Porro prisms with a clamping and rounding machine similar to that in figure 1.81. *a* Clamping axis, *b* direction of the pressure of the clamping bells, *c* Porro prisms, *d* template, *e* roller, *f* milling tool, *g* tension spring

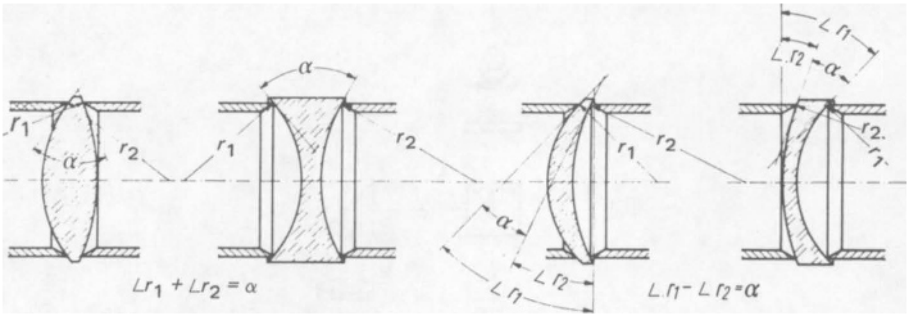

r1
α
r2
$\angle r_1 + \angle r_2 = \alpha$
α
r1
r2
α
r1
r2
∠r1
∠r2
∠r1
∠r2
α
r2
$\angle r_1 - \angle r_2 = \alpha$

Figure 1.87 Sliding angle α in different types of lens. $\alpha = \angle r_1 + \angle r_2$ for biconcave and biconvex lenses; $\alpha = \angle r_1 - \angle r_2$ for meniscus lenses

of friction μ between the polished glass and polished steel which is close to 0.15. According to the principles of the inclined plane, the coefficient of friction equals the tangent of the frictional angle that is also the sliding angle α, thus

$$\mu = \tan \alpha$$

So we have, for the limiting sliding angle $\alpha_{\min}$ for a lens that can just still be centred by the clamping pressure of the bells:

$$\tan \alpha_{\min} = 0.15$$

so

$$\alpha_{\min} = 8.5^\circ$$

Thus lenses with small sliding angles α should generally be centred by optical means.

The theoretical centring accuracy of the clamping method is a maximum when the sliding angle $\alpha = 180^\circ$, that is, in the case of a completely spherical lens! The curve of centring accuracy has been determined from this type of consideration at certain limiting points and is shown in figure 1.88. The sliding angle α is first calculated from the tangent angles between the curved surfaces at the bell diameters, then the centring accuracy corresponding to the sliding angle is read from the curve shown in figure 1.88. It is possible to achieve better accuracy than that shown in figure 1.88 under certain circumstances, but this is not generally possible in quantity production. The previous examples given for optical centring are re-examined here from the point of view of centring by the bell-clamping method.

Concavo–convex lens: $r_1 = 30$ mm, $r_2 = -70$ mm, bell diameter = 30 mm

$$\sin \angle r_1 = \frac{15}{30} = 0.5000;\ \text{hence}\ \angle r_1 = 30^\circ$$

$$\sin \angle r_2 = \frac{15}{70} = 0.2142;\ \text{hence}\ \angle r_2 = 12.5^\circ$$

$$\angle r_1 - \angle r_2 = \overline{\underline{17.5^\circ}}$$

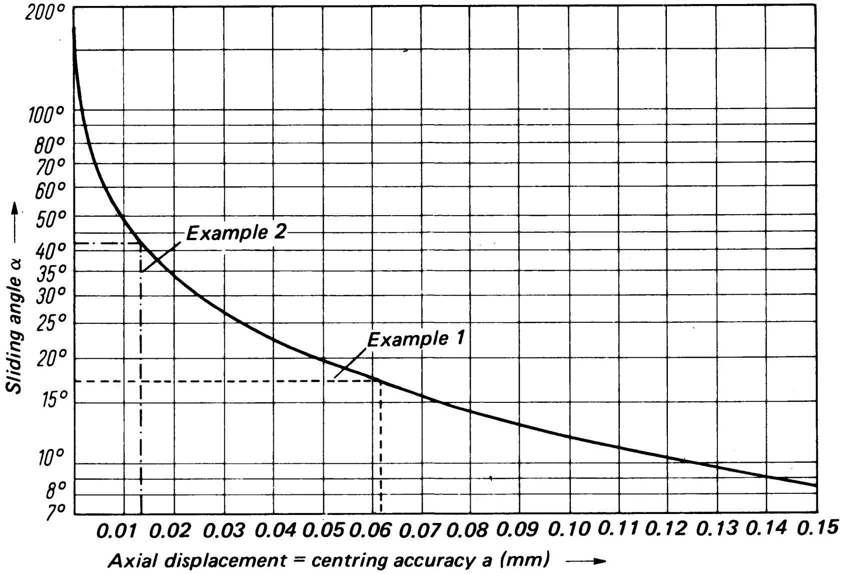


Figure 1.88 Centring accuracy that can be achieved by the bell-clamping method, as a function of the sliding angle

and for this value one obtains the corresponding value of accuracy from the curve of figure 1.88 at 0.062 mm.

Biconvex lens: $r_1 = 30$ mm, $r_2 = 70$ mm, bell diameter = 30 mm

$\angle r_1 + \angle r_2 = 42.5^\circ$ and therefore the centring accuracy

= 0.013 mm

Considering the process time, the bell-clamping method is very fast and simple, and it is therefore better to centre all possible lenses by this method if their tolerances allow. With the help of both the curves (figures 1.80 and 1.88), the engineer can decide whether a certain lens has to be edged using the bell-clamping method or by optical means, depending on the centring accuracy required. Also, for the purpose of tolerance calculations, it is essential to know the accuracy that can be achieved in centring with specific lens surface curvatures.

Operation 14: Chamfering of lenses

Normally, chamfers are required on all lenses on both sides. This operation is done when the lens is still on the mandrel, either by hand with a concave grinding shell (figure 1.89), or with a profiled diamond tool (figure 1.90). In the case of

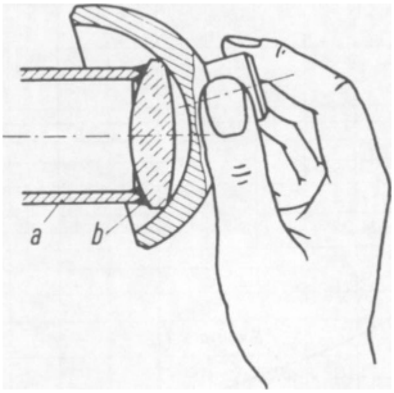


Figure 1.89 Grinding the chamfer by hand with a concave shell. *a* Centring/edging mandrel, *b* cement

requirements for special chamfer forms, particularly when these are required to run accurately with the lens edge, the latter method is preferred.

After chamfering, the lens is detached from the mandrel by a light mechanical shock and put in cleaning solvents.

In order to avoid chamfering by hand, the chamfers that are not specially required to be worked simultaneously with the lens edge are generated on a separate chamfering machine. In this chamfering machine the lenses are laid in the shells with emery and put into motion by centrifugal forces. Under the

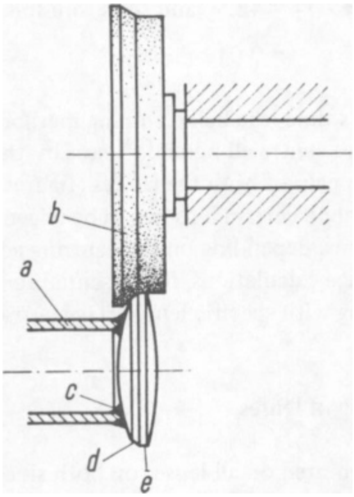


Figure 1.90 Milling the chamfer with a diamond tool. *a* Centring/edging mandrel, *b* chamfering tool, *c* cement, *d* chamfer, *e* cylindrical edge

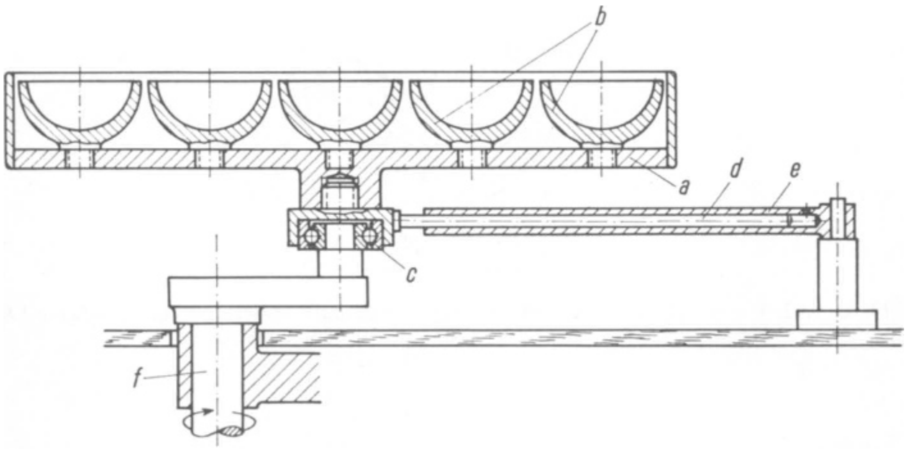


Figure 1.91 Chamfer-swinging machine. *a* Base plate, *b* chamfering tools screwed on the base plate, *c* ball bearing, *d* linkage shaft, *e* bearing for the linkage shaft, *f* crank drive

influence of centrifugal force and their own weight the lenses rub themselves against the emery in the shell and hence their sharp edges are removed (figure 1.91).

As many grinding shells as possible are attached to a large flat base plate. The plate is set with a ball bearing on a rapidly rotating eccentric spindle but prevented from rotation by a linkage shaft. In this way the centrifugal movement is obtained. The grinding shells are filled to approximately one-fifth of their depth with abrasive, water and a little glycerine, and the individual lenses are then placed in them. In accordance with the diameter and the weight of the lens, the rotation speed has to be adjusted so that the lenses swing out well, but do not go over the edge of the grinding shells.

The addition of 1 part of glycerine to 10 parts of water and abrasive mixture sufficiently hinders the evaporation of the water. The shell radius R_s should be chosen according to the formula

$$R_s = \frac{D}{2 \cos c}$$

so that a chamfer of the specified angle is obtained on the lens (figure 1.92). The running time of the machine for a particular size of the chamfer is dependent on the weight of the lens and the glass type, and must be determined by trial and error. When the desired size of chamfer is achieved, the machine should be switched off, and the lenses carefully picked from the shells with forceps, care being taken to avoid touching the spherical emery-covered surfaces.

The lenses are next cleaned under a water shower to remove the emery (figure 1.93), and then the lenses are cleaned with spirit and dried with a clean cloth.

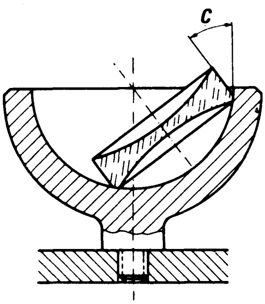


Figure 1.92 The chamfering angle while grinding on a chamfering-swinging machine (figure 1.91) for a lens of diameter D. c Chamfer angle

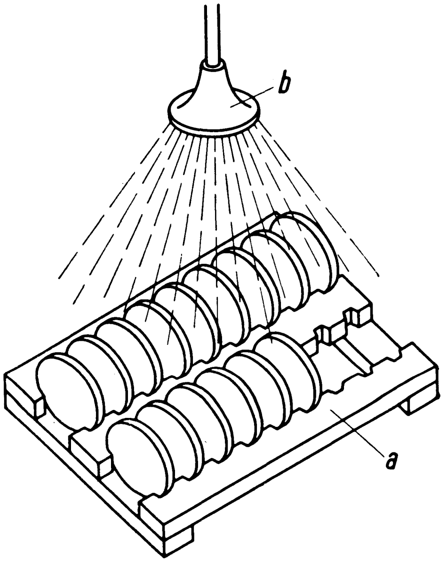


Figure 1.93 Rinsing the lenses. *a* Frame with notches for holding the lenses, *b* rinsing shower

Operation 15: Inspection of lenses

Lenses are brought to the inspection department in protective cases and as finished goods these must be inspected by trained craftsmen. The drawings are to be taken as the test specifications and appropriate standard documents show how the specifications are to be interpreted. It is not usual to check every lens for every type of dimensional error given in the specification drawing and the drawings must either specify the inspection procedure and the percentage sample to be taken, or the planning office must give special instructions in this respect to the inspection department. Under the supervision of an optician, assistant workers are trained for inspection work. Frequently these are women because of their softer hands and general suitability for clean, precise work. Every lens should be checked for cosmetic appearance and striae but, as regards other criteria, for example, thickness, diameter, figure (surface accuracy), centring accuracy, chamfer size, and imaging quality, only sample testing need be carried out, unless the drawing specifically states that a full examination is to be done for every piece.

The checking for appearance and striae can mostly be done with a 60 watt lamp and a X6 eyepiece ($f = 40$ mm). The workplace for the examination of cosmetic defects is screened from daylight because of the necessity for standard illumination. In the course of inspection, stains or blemishes on the surface of the lenses must particularly be observed and such components rejected, otherwise in the later stages of their manufacture, when vacuum evaporated or sputtered thin films are applied to the surfaces, these types of defect are found to be seriously enhanced.

The centring error and the imaging quality of individual components are checked when necessary with collimators, or on optical instruments which correspond in construction to the finished instrument in which the component under test is to be used. All the other tests are usually made with standard mechanical test equipment, for example, micrometers, ring and gap gauges or slip gauges.

Rejected lens components are, if possible, returned to the workshops for rectification. The proper conception and interpretation of the inspection work in relation to the quality of the finished goods is an important economic and technical factor in any factory. The manufacturing errors that are directly related to the performance of the optical instrument, for example, surface figure error, centring error and image quality defects, are assessed scientifically in accordance with the final requirements, and are checked by the inspection department accordingly. In this connection clarification can be had by referring to national or international standards for the performance testing of optical instruments.

The directions given in the standards for the assessment of appearance defects on glass surfaces are sometimes ambiguous, because the inspection in this case depends on subjective testing methods; hence, through ignorance, it is possible that a higher cosmetic standard is set than is necessary and this makes the finishing costly. This particular situation arises when engineering firms who do not have their own optical finishing shops, and whose technical staff are not acquainted with optics, wish to procure components from the optical industry.

The sizes of the permissible cosmetic defects depend on the position of the optical component in the ray path. If the component is at or near an image plane, the highest degree of appearance quality is required, because any one blemish can be a significant proportion of the instantaneous pupil and thus show in focus or as a shadow in the image. In the remaining optical parts of the instrument, almost any cosmetic blemish can be accepted as long as it does not (a) adversely affect the brightness produced by the instrument, (b) cannot be seen easily from outside the instrument and (c) does not reduce the image quality owing to scatter. These criteria should usually lead to an easily obtainable cosmetic standard. Although this is the requirement from a technical point of view, the salesman will sometimes have to insist on higher cosmetic standards to please the customers. This can often lead to significant increases in cost without any improvement in optical quality.

This frequently encountered situation requires the supervision of the inspection department by technically knowledgeable people who in the interests of production cost must resist any escalation in the fault-finding trend above normally specified standards, while at the same time not losing customers!

The education of customers in these matters is obviously important and very often a few simple demonstrations will clarify the situation for them. For example, a pencil held over the objective of a telescope of X10 magnification and 50 mm aperture will not usually make any visible difference to the image, so clearly a blemish a few microns in width will make absolutely no difference.

In the case of disputes over surface defects, standard markings have proved to be a useful practical means for comparison. The markings are made on glass plates with a diamond, as examples of the appearance of the usual range of grade numbers, and these are clearly marked with their actual scratch widths and lengths.

So far we have been talking about the appearance of individual optical components, which are to be assembled in the mechanical department. The assembly department refers to the delivery specifications for cosmetic standards that have been agreed with the customer, but often without any consideration of the standard appearance grades used for the individual optical components. This is not an ideal situation and there is usually a need to bridge this communication gap. At the very least the assembly mechanic must know that the optical parts are to be thoroughly cleaned and assembled free from any condensation, that is, vapour deposition from the surroundings. This can be cleaned off, and is not to be confused with stain which is formed on the glass because of its special chemical composition and which cannot be wiped off, but has to be removed with acids or by polishing. A typical condensation occurs in optical instruments because of unsuitable lubricants and also occasionally owing to transpiration from unsuitably porous pressure die castings used for the body of the instrument. When condensation is formed on one or more surfaces, then a part of the light passing through the instrument is lost. This loss can be measured directly with a photometer, and for this reason most testing departments check instruments by measurement of their transmission with a photometer, otherwise the adverse effect of this microcondensation can be seen by the human eye only in twilight conditions which again is a subjective assessment. The condensation occurring as a result of temperature changes in the closed instrument can be hindered only by a desiccating cartridge pack. The brightness and contrast of the images in optical instruments should be given many times more importance than the polishing scratches and sleeks on the polished surfaces. Condensation and stains have been particularly mentioned because untrained assemblers often mistake condensation for a surface defect of optical finishing.

Operation 16: Polishing correction of lenses

By further superficial repolishing the appearance defects detected by the inspection department can be rectified, and here one has to distinguish between surface stains, cleaning marks, sleeks, scratches and pits (digs).

Stains, cleaning marks and sleeks are removed by hand polishing work, because these defects often disappear after only a few minutes work. This superficial repolishing is usually done on a treadle bench, on whose spindle has been fixed the pitch polishing shell. The lens is held with the finger (figure 1.94). During this polishing, the permissible figure error limit of the lens surface must, of course, not be forgotten, because even by a short repolishing of a particular zone, the lens surface may easily deviate from its required form.

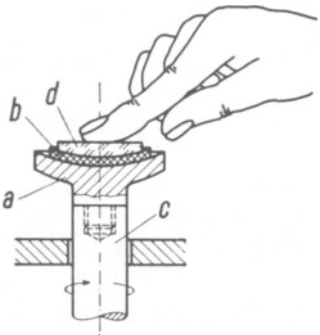


Figure 1.94 Superficial repolishing of a lens by hand. *a* Polishing shell, *b* polishing pitch layer, *c* spindle of treadle machine, *d* single lens

This latter error can easily arise when the polishing worker wants to remove quickly the stain on the outer zones of the lens, and in the process the central zone of the lens is not uniformly polished. To enable the polishing shell to give a uniform and immediate surface bite, it is immersed for a short time in hand-warm water, so that the pitch softens and is able to easily adjust itself to the form of the lens. When the polisher is taken out of the water the polishing shell is immediately fixed on the spindle and the lens laid on it and, under pressure of the finger, the pitch shell then takes the form of the curved surface of the lens. If the lens is now further polished, the figure of the lens surface need not suffer any change.

Marks, and fine hair-like scratches can also be removed by hand polishing, although the time taken for their removal is, of course, longer, depending on their depth. Often the fissures appear only as hair-like scratches, and then with a short superficial polishing (just for the removal of the glass burr) it can be verified if their depth requires a longer polishing time. The removal of coarse scratches by polishing takes much longer, and is conducted on a small lever-arm machine (figure 1.95). Depending on their form, the lenses are stuck on supporting tools, clamped in holders, or laid in a fixure that has a spherical socket on the

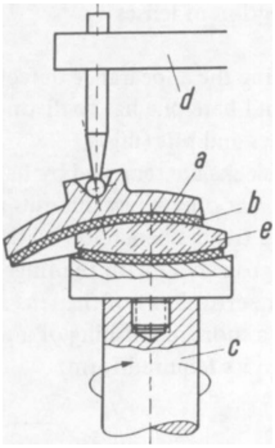


Figure 1.95 Superficial repolishing of a lens on a lever-arm machine (lens on top of the spindle). *a* Polishing shell, *b* Polishing pitch layer, *c* spindle of lever-arm machine, *d* lever arm of machine, *e* single lens

other side to be engaged by the ball pin and thus allow polishing underneath the lever arm (figure 1.96). In this way one worker can control up to twelve spindles. For the relaxation of the pitch shells to the desired form, hand-warm water is again used.

During the course of repolishing, the milled edges of the lenses come in contact with the polishing rouge which gives the edges a red colour that is not desirable for

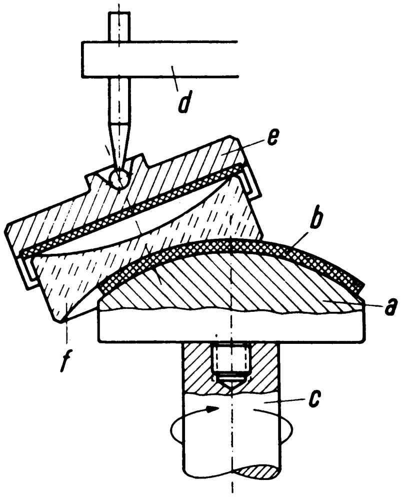


Figure 1.96 Repolishing of a lens in a holder on a lever-arm machine. *a* Polishing shell, *b* polishing pitch layer, *c* spindle of lever-arm machine, *d* lever arm, *e* clamping fixure for the lens, *f* single lens

the finished lens. The edges should therefore be protected with a lacquer that can easily be dissolved afterwards.

Any grinding or smoothing of centred lenses should be avoided if at all possible, because of the danger of centring and thickness errors being introduced. In the case of the careful smoothing of individual lenses, they are actually seldom afflicted with centring errors, but if the lenses are smoothed and polished as a block, centring errors arise frequently. It is then difficult to correct them and thus the resmoothing and polishing of centred finished lenses with the help of block holders requires a very careful blocking procedure so as to exclude the chances of centring errors.

The sticking of lenses on block holders in this instance has to be done in the same way as described in operation 8. However, the laying-in shell should be nearly polished and must be equal to the finished radius plus or minus the deviation in terms of interference rings required in smoothing, so as to make it possible to bite spontaneously all over the lenses in one superficial smoothing. In this way the lenses are uniformly reduced in thickness and are not decentred. Only in this way can the centring errors be kept to a tolerable level. Obviously the laying-in shell and the lenses to be blocked must be very clean, because a dust particle on the lens would lead to a centring error (and scratches) owing to its wedging effect.

Operation 17: Coating of lenses with reflection-reducing films

The production of reflection-reducing films on lenses is an evaporation or sputtering process and, because it is not the optician's job but belongs rather to the vacuum physicist, it is not covered here in detail. The optician is involved only insofar as he must ensure that the lenses are sent to the vacuum department with the best possible cleaned surfaces. Further, besides the highest degree of cleanliness, freedom from dust is also essential, and another cleaning process immediately before introduction into the vacuum chamber is necessary. In an air-conditioned, temperature and humidity controlled room, the lenses are thoroughly cleaned with spirit and napkins, or in an automatic ultrasonic cleaning chain, and are laid in special fixures ready for the coating plant.

A short while before the closing of the vacuum chamber, the last dust is blown from the surfaces with the help of a hand bulb. It is also recommended that a brush with a radioactive element should be used. This removes any electrostatic charge on the components with the help of ionising rays emitted from polonium foil.

During the evacuation process the optical surfaces are further cleaned by creating a glow discharge in the vacuum chamber which bombards the glass with cleansing molecules. In its simplest form the antireflection coating consists of a quarter wavelength (approximately 0.000125 mm) of magnesium fluoride evaporated on to the lens surfaces while they are heated to 300°C. The magnesium fluoride is supplied as a white powder which is evaporated from electrically heated molybdenum boats. The thickness of the film may be monitored during deposition by watching the characteristic colour of a reflection from a high refractive index monitor glass either by eye or with a spectrophotometric detector. When the coating is required for high efficiency at the blue end of the spectrum it will reflect relatively more green and red, to give a characteristic amber colour. For green light (visual) use it reflects more red and blue, which gives a magenta reflection, while for red light use it will give a characteristically blue reflection.

Magnesium fluoride has a refractive index in the region of 1.38 and operates most efficiently on high refractive index glasses which should theoretically have an index of $1.38^2 = 1.9$, which, of course, is unusually high. So for this reason, and others, more than one film is now usually used in a 'stack' of alternately high and low refractive index films which can reduce reflections to a very low level over wide chromatic bands.

Antireflection coating as a protection against stain formation on polished glass surfaces

The antireflection coating protects the glass surfaces to a certain extent against stain formation. Lenses that are made of glasses that are sensitive to stain formation are therefore coated with antireflection films even before centring them.

However, it should be borne in mind here that the antireflection film is not fully free from pores, and that the penetration of water vapour through the film can still cause the formation of stains.

Stain formation on optical glass

In respect of stain formation on optical glass, a great deal of research has been done and published by the scientists of many large optical firms, which gives practical suggestions for preventing the formation of stains. The real causes of stain formation lie mostly in the chemical composition of the air, the waxes and cements used, the gas flames, and the plaster of blocks, and in many other minor causes. The glass catalogues of manufacturers warn of the climatic resistance of the optical glasses in practical use, which can also be influenced during processing by the impurities in the atmosphere, though it may be difficult to notice the effect at the time. The real causes of stain formation lie in the properties and composition of the glass itself, and the practical man must adjust the processing materials accordingly to the type of glass. With a high degree of cleanliness and attention in all the processing and handling departments, and of course bearing with some accidents when certain components are adversely affected by humidity as a result of disturbances in the atmosphere, it is possible to bring sensitive photographic lens components unharmed to the antireflection coating stage which then provides further protection.

Operation 18: Optical cementing of lenses

In most optical instruments, lens systems are used that consist of one or more cemented lenses. These are cemented with optical cement in a dust-free room. Although most lenses are now cemented with cold cements, a description of the Canada balsam process is included here for completeness.

Cementing with Canada balsam

A walnut sized piece of Canada balsam is removed from a warmed flask with a peg-wood. The peg-wood with the balsam is kept in a cementing cupboard to protect it from dust, and it should be taken out only when required for the application of the cement.

The lenses are cleaned with spirit and napkins, dusted with a fine hair brush with the side to be cemented laid on the hot plate, and warmed up to the melting point of the balsam.

Next, the concave lens is lifted with the help of forceps from the hot plate, and the peg-wood with its balsam attached is taken from the cupboard. The concave side of the lens is held underneath, so as to avoid the chances of dust falling on to it, and the balsam is smeared over the surface until it spreads and is molten over the whole of the surface (figure 1.97).

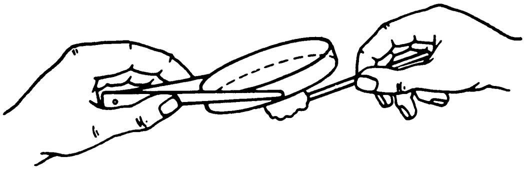


Figure 1.97 Smearing Canada balsam on the heated lens

The cement peg-wood is again put in the case, whose lid is actuated either with a foot pedal or with the hand that is holding the balsam peg-wood. The lens, with its concave side upwards, is laid on a sheet of clean paper kept on the hot plate and is covered with a glass bell jar for protection from dust (figure 1.98). Next, the matching lens to be cemented is picked up with the forceps from the hot plate, and the side to be cemented held underneath, then brushed (figure 1.99) and, after raising the glass bell jar, laid on the already balsam-smeared concave lens.

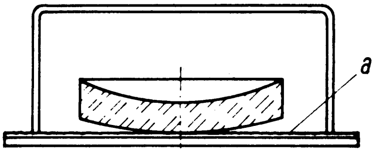


Figure 1.98 Glass bell jar for protection from dust. *a* Clean paper lining

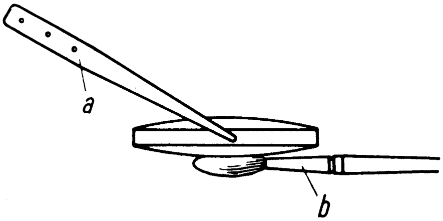


Figure 1.99 Brushing the convex lens. *a* Forceps, *b* brush

With a wood or cork pressing device the superfluous cement between the lenses is pressed out and, by oval movements of the top lens against the bottom lens, any air bubbles are also brought to the edge (figure 1.100).

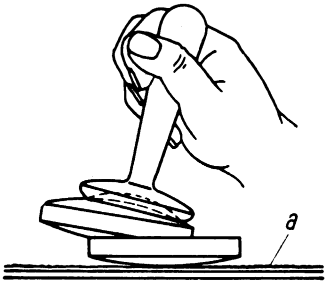


Figure 1.100 Pressing out the cement. *a* Soft cloth and paper support

Before the lenses cool down, their optical axes must be aligned with respect to one another. Mostly the accuracy is sufficient if the axes of the lenses are mechanically aligned, that is, when the lenses that have been centred and edged down to the specified tolerances with respect to their optical axis and diameter are put in a V-block to align their centred edges with respect to one another (figure 1.101). This alignment is subject to the condition that the limiting values to which the individual lenses have been edged are not any greater than the permissible centring error in the cemented system (figure 1.102).

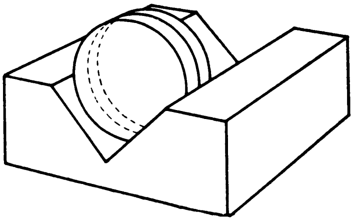


Figure 1.101 Alignment in a V-block

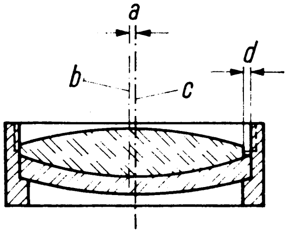


Figure 1.102 Possible centring error within an optical system as a result of unequal lens diameters. *a* Centring error within the system, *b* optical axis of the crown lens, *c* optical axis of the flint lens, *d* diameter difference between the lenses

It is apparent that for fine cementing, the method of alignment by optical means is potentially superior to mechanical alignment because, by alignment with transmitted light, the uncertainties through axial displacement and error in diameter or owing to any unimportant wedge effect in the cement layer are excluded. The alignment during optical cementing may be done with the help of an instrument that is similar to the optical centring instrument that is used for edging and whose layout ensures that the cemented doublet is tested with it in the way that is to be finally used in the finished instrument. The concave component of the pair of lenses to be cemented is held in a three-jaw precision collet which has been centred in the ray path of the accurately aligned centration testing instrument. The convex lens is then centred so that the collimator graticule cross-line is imaged on the double cross-line graticule of the viewing ocular. In certain specified cases, when both the lenses have centring errors, these must be rotated with respect to one another so that the centring errors compensate each other (figure 1.103).

A further method of observing centration is to examine the Newton's rings formed in the cement film. Although these are sometimes difficult to see, they are a sensitive and valuable clue to centration. After the centring, the lenses should be set aside to cool on a support that has been carefully levelled, so as to avoid the components sliding out of centration.

When the lenses are pressed during cementing, some cement protrudes out of the lens edges, and remains stuck to them. This is removed with a knife and the edges are then cleaned with methylated spirit or ether. The cemented lenses are next lightly stuck on some rotatable spindle with adhesive wax and, while rotating the lens, its edges are painted with a lacquer with the help of a hand-held brush or spray gun.

From the point of view of imagery, an optical system is complete only when, in a completely assembled state in metal mounts, it meets the test specifications. Thus the mounting of components in metal mounts requires particular care, so that an otherwise good optical system is not adversely affected in its imaging quality because of bad mounting. For this purpose the optical and mechanical

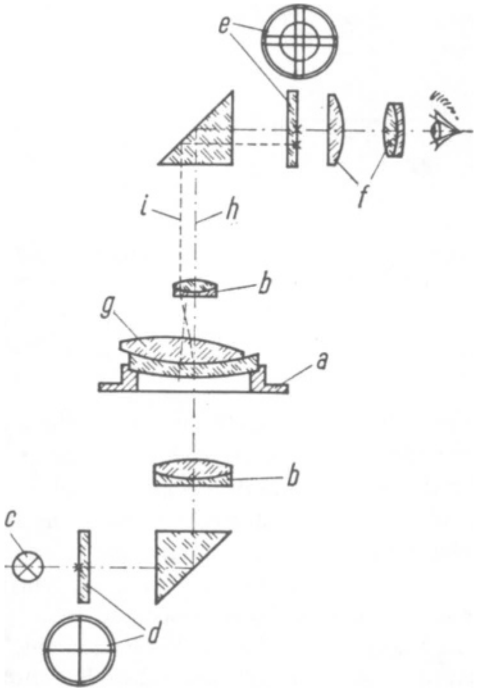


Figure 1.103 Optical cementing alignment instrument (schematic). *a* Centring collet for the lens to be centred, *b* optical system consisting of several achromats for imaging the collimator graticule on to the ocular graticule, *c* illumination of the collimator graticule, *d* collimator graticule or pin hole, *e* ocular graticule with tolerance circle, *f* ocular, *g* lens to be aligned, *h* ray path in centred and aligned lenses, *i* ray path in eccentric lenses

engineers must jointly decide whether a mechanical alignment would be sufficient, or whether alignment by optical means is essential.

Cold cementing methods

Originally, the cementing of optical parts was done only with thermally reversible cements (Canada balsam and cellulose caprate) and both the lenses and the cement had to be warmed during application. However, in case of necessity, the parts could also be easily decemented by warming them. But, since optical instruments are also required to be used in the tropics, and so are exposed to excessive heat, the parts held together with reversible cement can shift with respect to one another.

Generally, therefore, the optical industry has gone over to synthetic resin adhesives which are applied in the cold state. These cements are fully durable against water, benzene, acetone, and methyl alcohol. In the case of optical 'Araldite', for example, the cement remains unchanged between temperatures of –20°C and +70°C. 'Araldite' is an epoxy resin and its hardening is brought about by the addition of a separate hardener. With 'Araldite' there is no rapid splitting up of reaction products, and hence this cement is particularly suitable for polished surfaces. The basic resin and the hardener are delivered in a fluid state and they are mixed as required and applied with a hypodermic syringe. For application of the mixture to the lenses, the same rules of cleanliness that have to be observed in the case of cementing with Canada balsam apply. The low viscosity of the 'Araldite' allows the cemented layer to be pressed down very thinly, and the lenses can be aligned with the help of their finished edges, or by observing the Newton's rings in the cement film.

Another advantage of these adhesives is that the edges of both the cemented lenses can be simultaneously milled after cementing to obtain better overall centring accuracy of the complete doublet. For this purpose it is necessary to do an initial centring: first the concave lens is centred by optical means and edged down to a diameter a little larger than the final diameter required. This lens is then held in a three-jaw collet on the alignment instrument and the convex lens is aligned with it.

To harden the cement, it is helpful in the case of 'Araldite' to warm the assembly in an oven. Through this warming, the hardening time can be reduced to approximately five minutes. During heating, the temperature should not exceed 200°C, because above this temperature there is the danger of the 'Araldite' breaking. For the edging of the cemented lens system, the complete doublet is centred by either optical means or, in cases of sufficiently strong curvatures, by the bell-clamping method, and then the edges are milled down to the required diameter. By simultaneous edge milling of both the lenses, very clean edges are obtained which enable a very good fit to be achieved in the mechanical mount.

Since the introduction of 'Araldite' many other similar adhesives have been developed that offer even more attractive features. For example, 'Lens Bond' allows a relatively simple decementing which is not possible with 'Araldite'. There are also now cements that may be cured very rapidly with ultraviolet light. These are convenient mechanically but suffer the disadvantages that, unless the ultraviolet illumination is uniform, the cement film cures non-uniformly, so creating stress in the assembly. Also, in lens systems that require good blue light transmission these ultraviolet-setting cements tend to absorb light at that end of the spectrum.

Operations 19 and 20: Final inspection and pairing of components

The final inspection of different lens systems with respect to their appearance and technical parameters is done as in operation 15 in accordance with given specifications. Particular care is taken in detecting any bubbles or dust particles in the cement and also any breaks in the cement film at the edge of the components. In the case of the pairing of lens systems, for example, for binocular instruments, it is often essential to sort and pair them according to thickness or focal length and, in order to avoid mixing up later on, the edges of the lenses of paired systems should be marked with their pair number by means of a diamond pencil.

If, because of its optical design, a lens system is capable of delivering a corrected image, then the final inspection in respect of its image quality is an important control point. In accordance with the requirements and specifications of an optical system, its image evaluation has to be done for the axial rays and/or for oblique ray paths. In the case of testing imagery for the axial image point, the lens system is usually placed so that it looks at a collimator that has a pin hole or a test object at its focus and, with the help of a microscope, the image formed by the lens system under test may be observed on a rotating ground glass screen (figure 1.104). The ground glass is made to rotate so that its grinding marks are made to disappear. In the ideal case the pin hole is imaged as a clear sharp point whereas, in the case of non-exact point image formation, a brighter ring may be formed around the point, or an elongated imaging of the point may occur. It may well then be interpreted as being caused by zonal errors or by astigmatism

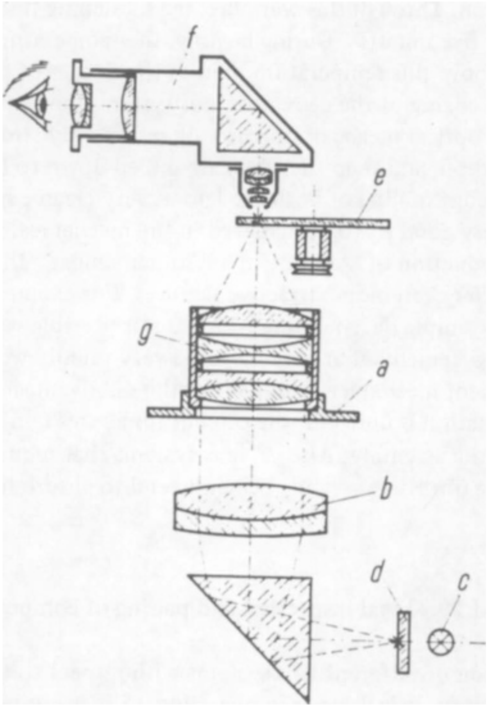


Figure 1.104 Testing a completed optical system for axial imagery (schematic). *a* Centring collet for mounting the lens to be tested, *b* collimator objective, *c* illumination for the collimator graticule, *d* collimator graticule or pin hole, *e* rotating ground glass disc, *f* observation microscope, *g* lens under test (complete photographic objective)

respectively. By introducing apertures of different diameters in front of the system under test, one can determine the zone causing the bad imagery.

For testing oblique ray paths (extra-axial imagery), the arrangement is also similar to that used for testing in the direction of the axis. The oblique ray paths may be obtained by the tilting and positioning of a mirror, and for the observation of the image the same microscope may be displaced (figure 1.105).

With this apparatus, the completed objectives may be tested and, in the case of defects in their imaging quality, the objectives may at the same time be re-adjusted with the help of the apparatus. A large proportion of the defects in imagery can be traced to the centring errors that arise in complicated mechanical assembly mounts, mostly owing to displacement errors. It is sometimes possible to neutralise centring errors by shifting one lens of the system. The optical designer can usually judge and advise which lens of the system is best suited for this purpose. The shifting arrangement may be implemented by making the mechanical design in such a way that two eccentric rings rotate with respect to one another around the mount of the lens that is the most suitable for corrective displacement. This technique is seldom as practical as ensuring that the individual components and subassemblies are correct before they are finally assembled.

Generally the diagnosis of system errors is greatly assisted by the simple categorisation of image errors. For the axial image, astigmatism (two perpendicular focal lines instead of a single focal point) is a clear indication of irregular lens polishing or a strained mirror, as a result of clamp rings being tightened too much.

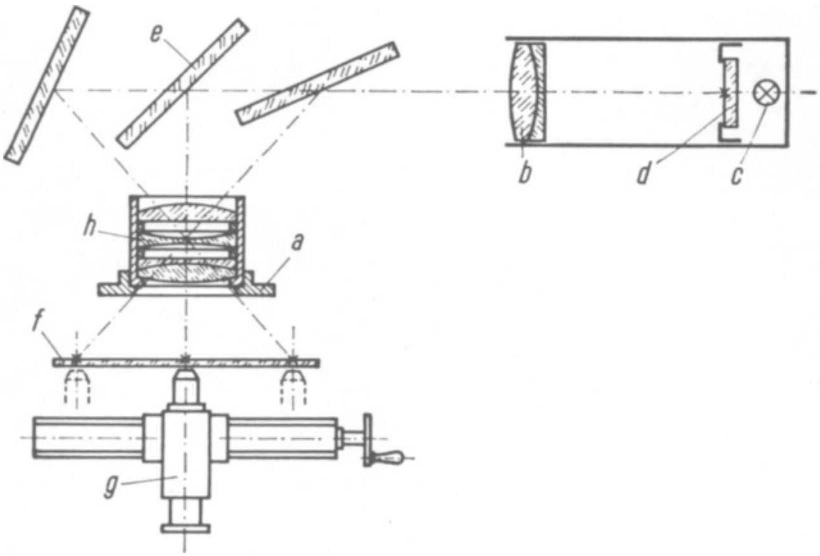


Figure 1.105 Testing a completed optical system for oblique ray paths (schematic). *a* Centring collet for mounting the lens under test, *b* collimator objective, *c* illumination of collimator graticule, *d* collimator graticule or pin hole, *e* adjustable mirror, *f* ground glass disc, *g* observation microscope, *h* lens under test (complete photographic objective)

If there is no astigmatism present on the axis there may, however, be coma (an asymmetric fringe at the focal point). This is best viewed with a high microscope magnification, and it is a sign of a decentred or tilted component. This error may be more easily detected if the lens is rotated about its optical axis; such a rotation will generally move the pin-hole image in a circle, which is not in itself important – it is the constancy of the moving image that is important.

For the off-axis points, rotation of the optical system about its optical axis is of great assistance in observing image errors that result from decentred components. The off-axis image will in any case exhibit coma and astigmatism in accordance with the design intention, but it is the variation of these aberrations as the lens rotates that is of interest (again, not the movement of the image, but its aberrational variation). Spinning the lens while viewing the off-axis image points is particularly sensitive to tilts and decentrations in components that are at some distance from the optical systems aperture stop.

2

Manufacture of Photographic Objective Components on Hard Block Holders (28 operations in accordance with table 2.1)

The pitch-pellet sticking method described in chapter 1 is best adapted to the manufacture of small batches of components, because the inconveniences involved in the method are compensated by the low cost of the tooling; this low cost arises from the adaptability of a single set of shells and block holders for lens components of different shapes and sizes.

In the case of large batch sizes it is more economic to bore precision recesses in a block holder, in order to accommodate each specific component. Such an arrangement allows one to wax lens components in position, generate the curves with a diamond mill and then proceed directly to smooth grinding and polishing. An additional cost that may often be incurred when this process is used is the result of having to pre-edge and/or trim misshaped lens moulds.

The control and processing of raw glass through the stages of scoring, weighing, moulding and annealing is particularly important in the case of glass intended for photographic objectives because the lens design often has to be adjusted to accommodate the precise refractive indices of each of the glasses used. These indices depend on the meltings supplied by the glass manufacturer and the annealing schedule applied to the moulds.

Before placing the order on the workshop the planning department must submit the glass melt record sheets to the optical designer, who must adjust the design as necessary to allow for the variations of refractive index and dispersion between the different melts. This usually involves subtle changes to surface curvatures, centre thicknesses and, at the assembly stage, separations. These subtle changes must be recorded on working drawings, and where more than one set of melts is involved in a batch, careful segregation of subtly different components must be rigorously maintained in the workshops.

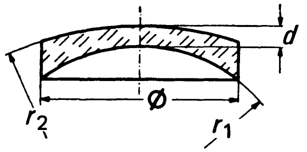
The optical designer should avoid changing surface curvatures for the purpose of melt compensation because this may split an economic batch size and significantly increase costs, whereas centre thicknesses and separations may be adjusted relatively inexpensively.

Table 2.1 shows the scheme of manufacture for photographic objective components when hard block holders are available. The process of making mouldings and the witness marking method for obtaining precise lens thicknesses are both described, while the remaining operations of grinding and polishing have already been described in chapter 1. Notes on the manufacture of hard block holders are also given.

Table 2.1 Layout for manufacture of lenses on hard block holders

Type of job:
convexo–concave lens

Sketch:



Drawing no.:

	Operation	*Layout specifications*
1	Issue of material	Glass type: Piece size: glass disc with no. n_d tolerance: Piece thickness: Bubble tolerance: weight:
2	Slitting	Glass block to be slit into plates Thickness and tolerance in accordance with the sizing table
3	Sizing/squaring	Piece size should be adjusted according to the plate thickness and as recommended in the sizing table. Weight of the raw piece:
4	Checking the glass pieces	Check for bubbles and striae Bubble tolerance: Striae tolerance:
5	Scouring in drum	Corners and edges to be abraded in a rotating scouring drum
6	Adjusting the weight	Glass cracks to be ground out and the blanks to be reduced to the specified weight

Table 2.1 *Continued*

	Operation	*Layout specifications*
7	Moulding	Press tool no: Softening temperature: Glass type:
8	Cooling and annealing	Strain-free cooling in the annealing oven Cooling temperature rate of change:
9	Examination of the pressed blanks	Strain and pressing defects to be checked with polarised light
10	Milling of witness marks	Mill witness marks on the required number of witness lenses Thickness: Four witness-marked lenses for every block holder
11	First lens side waxing	Block holder no.: Type of wax: Four witness-marked lenses to be stuck on every block holder
12	First side milling	Concave radius: Milling tool number: Size of witness mark:
13	First side grinding	Concave radius: Type of grinding material: Size of witness mark: Number of interference rings:
14	First side polishing	Concave radius: Machine type: Pitch type: Cosmetic quality: No. of interference rings: Irregularity tolerance:
15	Lacquering and unblocking	Polished surfaces to be painted with protective lacquer, and block holders to be heated to release the lens components
16	Milling of witness marks	Witness marks to be milled on the convex side of witness lenses Thickness: Four witness-marked lenses for every block holder
17	Second lens side waxing	Block holder no.: Type of wax: Four witness-marked lenses to be stuck on every block holder

Table 2.1 *Continued*

	Operation	*Layout specifications*
18	Second side milling	Convex radius: Milling tool number: Witness mark size:
19	Second side grinding	Convex radius: Abrasive type: No. of interference rings: Witness marks size:
20	Second side polishing	Convex radius: Machine type: Pitch type: Cosmetic quality: No. of interference rings: Irregularity tolerance:
21	Second side unblocking	Heat the block holder
22	Lens cleaning	Dissolve the blocking wax by placing the lenses in soaking containers or in an ultrasonic cleaner
23	Centring	Machine type: Centring method: Diameter: Axial displacement: Chamfer size:
24	Chamfering the lenses	Machine type: Chamfer angle and size:
25	Inspection of lenses	Radius 1: No. of interference rings: Radius 2: No. of interference rings: Thickness: Diameter: Axial displacement: Chamfer:
26	Rectification	Rectify as indicated by the inspection department
27	Coating the lenses	Apply reflection-reducing films as specified by the physicist
28	Final inspection	According to drawing

Operation 1: Issue of material

This is essentially the same procedure as described in chapter 1, with any additional precautions dictated by the occurrence of melt-sensitive components.

Such is the importance of segregating lens components which are apparently similar but which are manufactured from significantly different glass melts, that it is vital that a reliable system of melt identification is used. In some factories a piece of scrap glass from the melt concerned is issued with the raw glass; this piece of glass is clearly marked with the melt identity, and in the case of a mix-up it may be used as a refractometer sample for comparative refractive index measurements.

Operation 2: Slab glass cut into slices or discs

This operation has already been described in chapter 1, but there it was not intended that the glass should be moulded, and in that case the thickness of the slices was determined by the thickness of the final lens component. For the economic production of lens components for photographic objectives, where the surface curvatures are deeper, and where hard block holders are to be used, it is vital that the glass be supplied from the manufacturer as moulds or that the lens factory moulds its own glass. This is particularly important where the more expensive optical glasses are involved, as long as they are suitable for moulding.

The thickness of the slices is determined by the fact that the square pieces should have a diagonal smaller than the diameter of the moulding tool but should be of the same volume as the finished lens mould. This is so that the piece of glass may be laid in the moulding tool (see figure 2.1).

Because the glass manufacturer cannot always supply slab glass of a standard thickness, the economical slitting into plates of equal thickness from any one block means that the rectangular pieces should be of different sizes to achieve equal volumes.

For ease and convenience the glass cutter should be supplied with a chart of

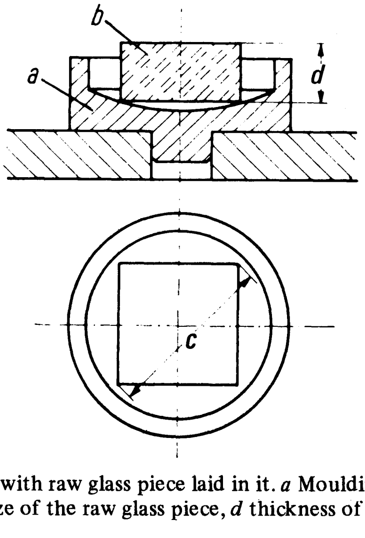


Figure 2.1 Moulding form tool with raw glass piece laid in it. *a* Moulding form tool, *b* squared raw glass piece, *c* diagonal size of the raw glass piece, *d* thickness of the raw glass piece

square sizes corresponding to lens moulds of particular volumes, given a plate of a particular thickness. This avoids the labour of calculation, reduces mistakes and enables the glass cutter quickly to select the preferred direction for cutting each block.

Again, a check must be made of the melt number on the slab before the first cut is made.

Operation 3: Squaring and sizing

The basis of this operation has been described in chapter 1, but when it is intended that the glass pieces will be moulded a further point should be mentioned.

The sizing chart should provide weights as well as volumes so that the glass cutters can check their work with weighing scales. The weight of the glass pieces should be given with a positive tolerance because they lose some of their weight in the tumbling process.

Operation 4: Inspection

This is the same as operation 5 of chapter 1.

Operation 5: Tumbling process for smoothing

The sharp corners and edges of the cut pieces can produce defects in the final mould, and should be removed by a drum tumbling process with water and abrasive (figure 2.2).

Again, it must be remembered that glass pieces from only one segregated melt should be tumbled at any one time to avoid mixing melt-sensitive glass pieces.

Operation 6: Adjustment of weight

After tumbling, the glass pieces are washed in water and individually weighed. The

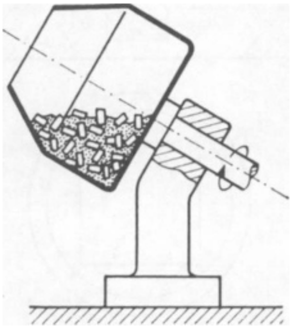


Figure 2.2 Scouring drum

required weight is given on the sizing chart, and should any piece be too heavy it may be ground on a carborundum wheel to reduce its weight.

Next the glass pieces are passed to the moulding department, their melt identity having been checked again.

Operation 7: Moulding

This process requires that the glass pieces be heated to their softening point, or a slightly higher temperature, depending on the shape of the required moulding. The moulding die should be maintained at the temperature of the glass pieces or higher, and when the finished moulding is removed from the die it should be allowed to cool gradually. The craftsman who does this work has a hearth and an oven and he can heat the glass pieces and the dies, do the pressing and put the mouldings to cool slowly in the oven, as a continuous process.

The requirements of hearth and oven can be met by a specialist pressing oven as shown in figure 2.3. This equipment consists of an initial warming chamber, a high-temperature warming chamber, the pressing hearth and a cooling-off container.

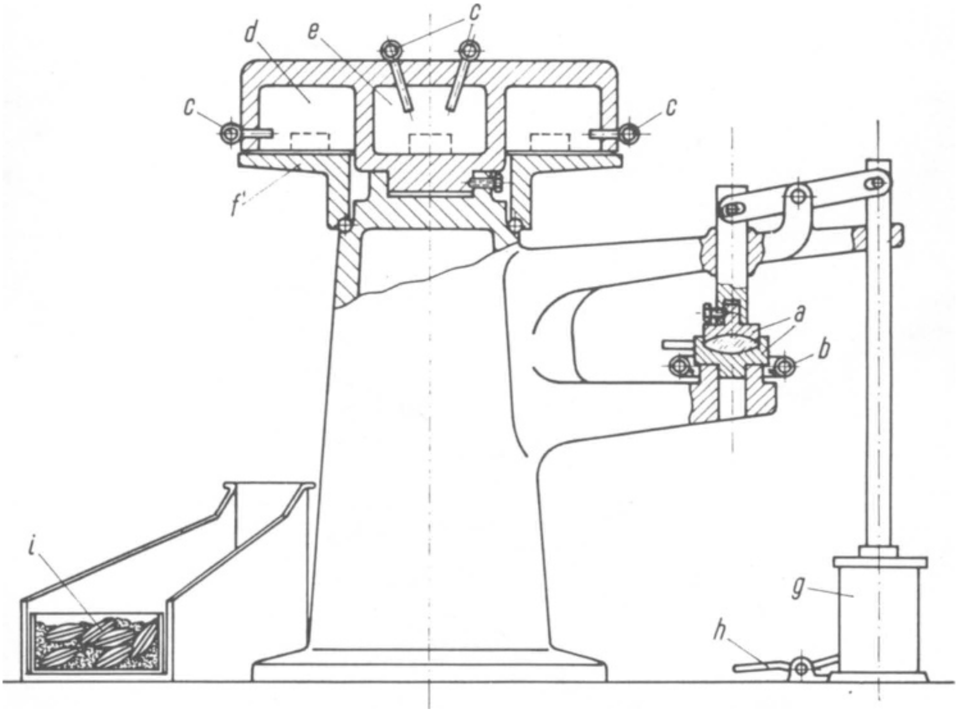


Figure 2.3 Schematic sketch of a moulding oven for lenses and prisms. *a* Moulding die, *b* gas ring burner for heating the moulding die, *c* gas burner for heating the raw glass pieces, *d* initial warming chamber, *e* high-temperature warming chamber, *f* rotating base of the initial warming chamber, *g* compressed air cylinder for operating the moulding die, *h* foot lever for the press, *i* cooling-off container with sand filling

The various tools required to manipulate the glass pieces are shown in figures 2.3–2.6 and figure 2.7 shows their combined use.

The sequence of operations is as follows: the cold glass pieces are placed in the initial warming chamber which is provided with a fire-clay base plate that has been preheated and dusted with graphite to avoid the glass pieces sticking (special fire-

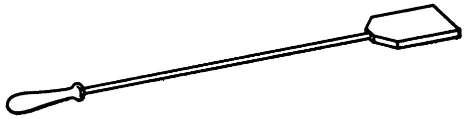


Figure 2.4 Pushing poker

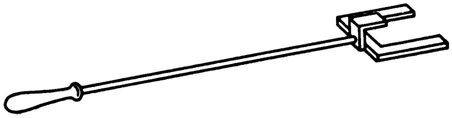


Figure 2.5 Carrier for supporting base

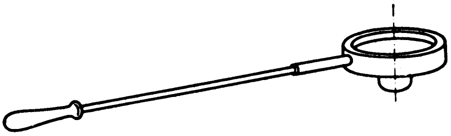


Figure 2.6 Die and moulding ejector

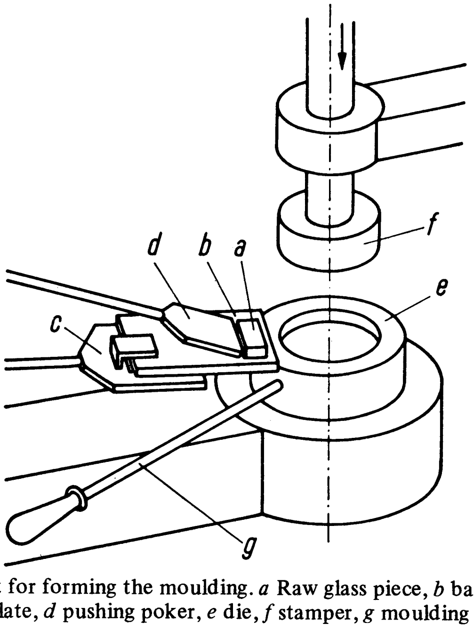


Figure 2.7 Equipment for forming the moulding. *a* Raw glass piece, *b* base plate, *c* carrier for base plate, *d* pushing poker, *e* die, *f* stamper, *g* moulding ejector

clay with a non-stick surface can also be used). The base rotates to bring the glass pieces slowly into the higher temperature area of the oven, and when the cycle is complete they are moved over into the higher-temperature oven, and a new charge of cold glass pieces is placed in the initial warming chamber.

The higher-temperature oven brings the glass pieces to a plastic state, when they can be brought to the die and pushed in with the aid of the poker.

The pressing operation is achieved with a foot-operated compressed air system which brings the upper half of the die down on to the glass piece. When that is complete the craftsman can tip the completed moulding out into the sand-filled cooling-off container, where there should be enough sand to insulate the hot mouldings and retard their cooling to avoid their cracking.

Careful attention to the temperature regulation of each section of the equipment, and the rate of flow of the work, adjusted to the size and glass type involved, is vital if a good yield of tidy mouldings is to be achieved.

Operation 8: Cooling

The initial cooling off is a crude process which merely avoids the glass pieces cracking, but the final moulds must be free of thermal stress (as checked with a polarisation stress viewer) and to be in this condition they must be subject to a more or less prolonged cooling schedule (annealing), starting at the softening temperature. After soaking at that temperature for some time the temperature is slowly brought down to room temperature.

The moulded pieces are taken out of the cooling-off container of the moulding oven, and repacked neatly with sand in the annealing trays, care being taken to ensure that each moulding is completely surrounded by sand.

The annealing trays are then stacked in a pile as shown in figure 2.8, and the heated bell cover is brought down over them as shown in figure 2.9.

The annealing schedule depends on the glass types involved and the size of the mouldings. Large mouldings of sensitive glass types can take many weeks to anneal.

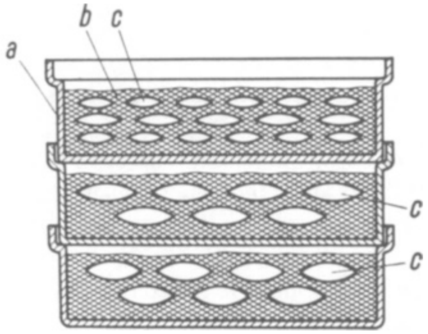


Figure 2.8 Stacked annealing trays. *a* Stacking trays, *b* special sand packing, *c* mouldings

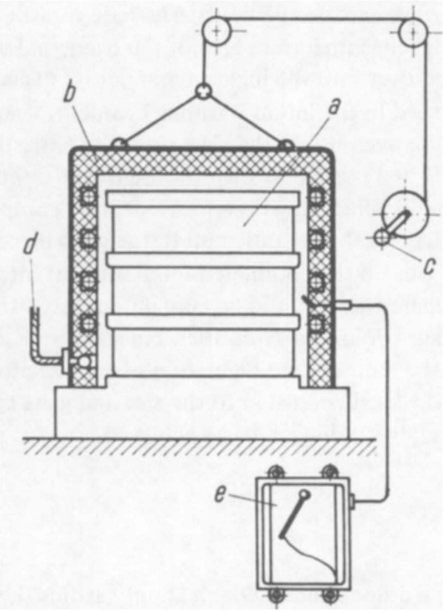


Figure 2.9 Annealing oven. *a* Stacked trays, *b* hot bell cover, *c* crank for raising and lowering the cover, *d* electrical connection, *e* thermostat and recorder

The precise cooling schedule will affect the final refractive index and in large-scale manufacture of optical systems with melt-sensitive components this can be used to adjust the refractive properties of the glasses involved, so as to avoid the adjustments of thickness and curvature that would otherwise be necessary.

The cooling process is controlled by automatic temperature regulators with a chart recording. Care must be taken to avoid the mixing of different melts of the same glass type if this is important, although useful economies can sometimes be achieved by packing different mouldings of obviously different shape in the same tray. Obviously, only glasses with very similar cooling temperatures can be passed through the same annealing schedule.

Operation 9: Inspection for stresses and moulding defects

If there is any residual stress in the mouldings this can be detected using polarised light, because the stressed glass alters the state of polarisation of the light passing through it. A typical viewing arrangement is shown in figure 2.10, which shows a piece of black glass used as a polariser, and a Nicol prism used as the analyser, with a gypsum plate at the eyepiece to improve the colour contrast of the birefringent effects in the glass mouldings under test.

If the mouldings to be tested are wetted or moistened, the surface irregularities

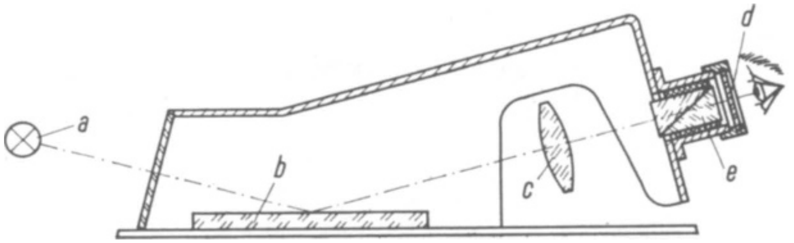


Figure 2.10 Optical stress viewer. *a* Light source, *b* polariser, *c* moulding under test, *d* gypsum plate, *e* analyser

are effectively removed, so improving the visibility of the internal effects due to stress, and also the moulding defects such as cracks or bubbles.

The dimensional characteristics of the mouldings should also be checked for thickness and surface curvature. Measuring the thickness effectively checks the weight of the glass pieces that were used. The surface curvatures can be checked using templates.

The identification marks on the mouldings should also be checked.

Operation 10: Milling witness marks

When lens components are manufactured using the pitch pellet method it is necessary to check and correct centre thickness after the first side is polished, so that when the second side is polished the final thickness is achieved. In the case of lenses manufactured on hard block holders it is not necessary to perform this correction process if witness marks are milled in the moulding before they are blocked up. This process contributes to a smooth and efficient flow in the production process, which is vital if large quantities of lens components are to be manufactured.

These witness marks are applied to both surfaces of the moulding, as shown in figure 2.11. The centre thickness *t* is the final thickness plus the tolerance on the centre thickness. Such witness-marked pieces are distributed over the block as shown in figure 2.12, that is, one in the middle and three equally spaced around the block at a zonal radius towards but not at the edge of the block. Obviously, only a proportion of the mouldings have to be witness marked.

During the milling and grinding processes these witness marks should be reduced steadily and uniformly, so demonstrating the state of tuning of each stage of the

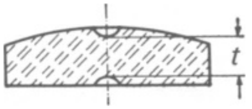


Figure 2.11 Blanks with milled witness marks. *t* Finished thickness plus working allowance

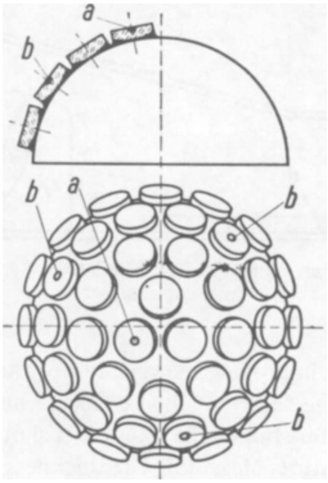


Figure 2.12 Distribution of witness-marked lenses on the block holder. *a* One witness-marked lens in the centre, *b* three witness-marked lenses between the centre and the edge

processing, particularly with regard to the radius of each successive grinding tool.

The witness marks are milled with a special machine as shown in figure 2.13. The mark that is made indicates the progress of the grinding with greater sensitivity as the final stage is approached, owing to the flat-bottomed shape of the witness depressions.

The mouldings that are to have witness marks are individually clamped in the collet, which locates on the moulding in the same fashion as the recesses in the block holder. The milling cutter is then lowered manually until the feed limit screw reaches the stop. In this way the lens mouldings are given witness marks at a uniform height from the lens moulding datum edge. It is, of course, necessary to set the feed stop using a master lens component of the appropriate thickness.

For particularly precise work it may be necessary to arrange for the witness marking of the second side to be achieved after the first side is complete, because only in this way can the collet of the machine simulate the location of the lens on the hard block holders.

Mineral oil is used as a cutting fluid during this operation.

Operation 11: Sticking lens components on the hard block holders for first side processing

The warmed lens blanks are cemented on to the hard block holders with waxed wafers which are softened by localised heating of the block holder. In this way the operator can work systematically and quickly, so reducing costs.

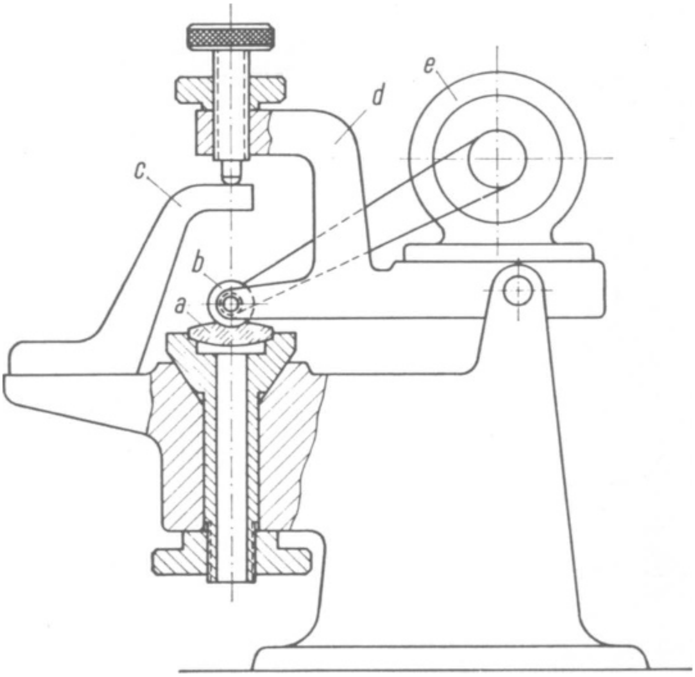


Figure 2.13 Witness-mark milling machine. *a* Lens clamped in collet, *b* diamond milling tool, *c* feed stop, *d* tilting arm for milling tool, *e* motor drive

The design of hard block holders

The hard block holders are, of course, tooling fixtures whose accuracy is directly transferred to the components, particularly to the centre thickness of the finished lenses. For this reason the block holders must be manufactured in a tool room machine shop with due regard to appropriate geometrical tolerances, which in many cases are very tight.

The designer of the hard block holders must have experience of optical processing. Part of the task resembles the traditional work of laying out pitch pelleted lens blanks on a fine grinding tool prior to blocking, and the priorities of that situation should be well known to the designer.

The usual requirement is for there to be as many components per block as possible, without them touching each other, or without the overall angular occupancy exceeding approximately 170°.

There are several well-known formulas for the selection of the nominal lens component layouts, but the detailed design for lens components of substantial thickness is best completed with careful drawing board work. This design work is, of course, applicable to the pitch pelleting method as well, and useful guidance can often be given to the glass processing workshop for that work.

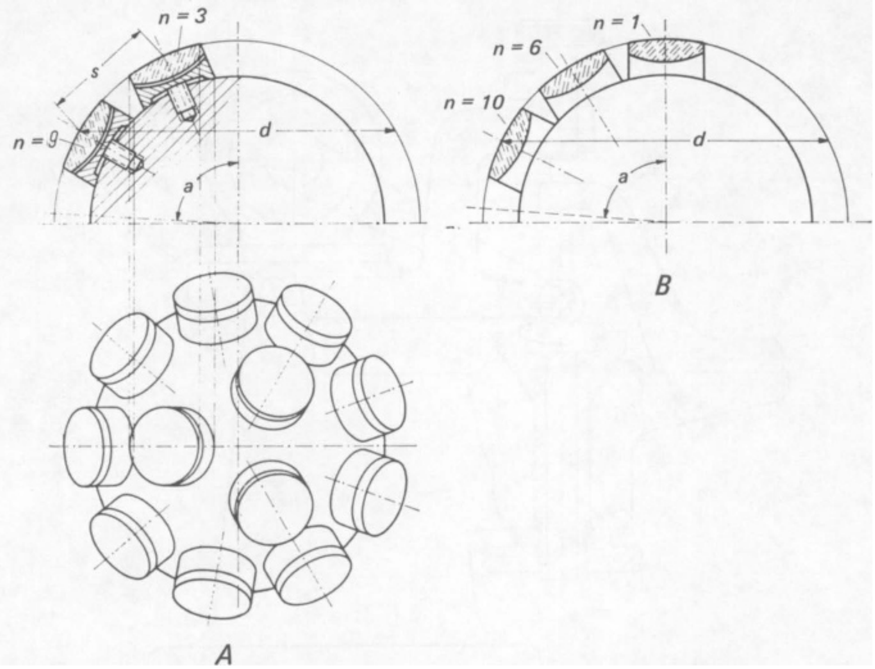


Figure 2.14 Design and construction of hard block holders. (A) Block holder with three lenses in the centre, yielding twelve pieces per block (preferred for high surface quality components). (B) Block holder with one lens in the centre, yielding 17 pieces per block (preferred for low surface quality components): *s* distance between the lens centres, *d* diameter of pitch circle, *a*, occupation semi angle, *n* number of components in any one ring

Figure 2.14 shows the design of two alternative convex blocks with 12 and 17 lens components each. In the case of lens mouldings there will be 0.7–0.8 mm of extra material on each face, and an allowance on diameter for final edging that will depend on the focal power of the component and the tolerances to which the tooling is to be made (so that the 'wedge' of the polished component may be taken out at the edging stage). Thus, the glass component involved in the design of the block holder is significantly bigger than the finished lens.

The first consideration in the design is whether it is possible to avoid a single component in the middle of the block, because such a component will usually exhibit surface shape irregularities introduced at the polishing stage. In the case shown in figure 2.14, five extra components may be processed if one of them is allowed to be in the middle but, depending on the glass material, cost, surface shape tolerances and so on, it may be appropriate to select either one or the other of these layouts.

The design procedure can proceed as follows. A semicircle representing the finished polished surface is drawn as the elevation, and a circle of an appropriate diameter for the plan view.

Bearing in mind the thickness of the mouldings and the support buttons, a further semicircle is drawn on the same centre to represent the surface of the hard block holder.

Trying either three lenses in the middle or only one, the closest approach of the buttons or machined recesses may now be determined on the plan view. Care should be taken to ensure that under conditions of worst case machining errors the buttons cannot touch each other, because this would lead to serious local errors of surface shape at the polishing stage.

In the case of concave optical surfaces, this step only involves checking that the circles (or ellipses) representing the surfaces of the glass mouldings before machining do not touch in the worst case of tolerance build-up.

When the circumscribing circle of the three central lens components (or the diameter of the mould when there is only one central piece) has been defined, the outer rings of components may be located on the elevation, and the approximate number of lenses in each ring can be determined from

$$n \simeq \frac{180^\circ}{\sin^{-1}\left(\dfrac{s}{d}\right)}$$

This equation is only approximate and it tends to be optimistic about the number of lenses that can be placed into any ring, but the value of n must in any case be the whole number just less than the value calculated from the formula. Where the theoretical value of n is only slightly less than a whole number it will not normally be possible to squeeze the larger whole number of components into that ring, although this depends on the precise geometry of the seatings.

It is difficult to give rigid rules in this situation, but where putting three components in the centre of the block leads to underoccupancy of the full diameter that might be used, it is usually fruitful to consider the block layout based on one central component.

The design of concave block holders does not involve any different principles and need not be described separately.

When block holders for first side processing are being designed the thickness of the lenses and the build-up of tolerances on support buttons are not so important. However, block holders for second side processing must be much more carefully toleranced, with due attention being paid to the thickness of the blocking cement, so that the sum total of the basic block holder surface radius plus the thickness of the supporting buttons plus the thickness of the cement plus the finished centre thickness of the lens is equal to the final polished radius (figure 2.15).

Considerable care must be exercised in specifying the machining tolerances in this situation. Each of the buttons should be of equal effective thickness, the spherical datum of the hard block holder must be of the correct radius, and the design of the feet of the buttons must allow reliable location against this spherical datum. The centre line of the main mounting shank should also pass through the centre of curvature of the spherical datum and it should be provided with a

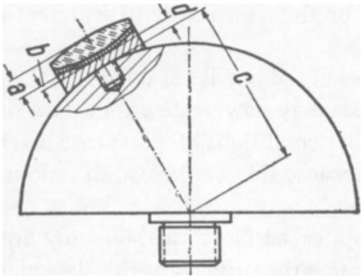


Figure 2.15 Thickness of support buttons on hard block holders. *a* Finished thickness of lens, *b* thickness of cement wafer, *c* hard block holder radius, *d* thickness of support button

substantial cylindrical datum surface and shoulder, so that it may be located interchangeably in the processing machines for milling, grinding and polishing.

Care should also be taken to engrave each tool with the part number for which it is required so that they do not become mixed up.

If appropriate machining tolerances are applied in this way, the most variable factor determining the final lens centre thickness will be the wax wafer used to cement the glass component to its button.

The manufacture of cementing wafers

Figure 2.16 shows the arrangement of a machine suitable for producing cementing wafers of a uniform thickness.

Obviously, a most important factor in achieving uniformity of thickness is the selection of a paper or cloth that is naturally uniform in thickness. The selected

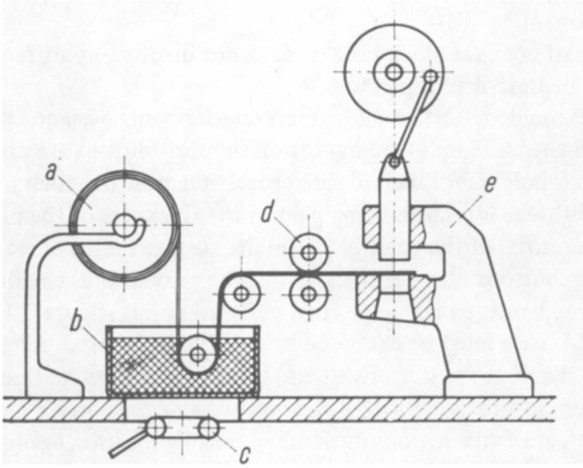


Figure 2.16 Arrangement of equipment for the manufacture of cementing wafers. *a* Cloth or paper roll, *b* cement tank, *c* cement tank heater, *d* transporting rollers, *e* stamping press

material will normally be supplied in a roll, and this is mounted on the machine as shown in figure 2.16 at *a*.

The paper or cloth strip is impregnated with hot wax and then cooled prior to being brought on to the stamping stage as shown at *e* in figure 2.16.

A suitable cementing wax may be prepared from a mixture of shellac and rosin, to which a small quantity of beeswax, or paraffin wax has been added. The precise quantities of these three constituents depend on the qualities that are selected, but the important characteristics are that at 60°C the cement should be completely fluid, at 30°C it should be completely solid, and at 0°C it should be sufficiently brittle to facilitate spontaneous separation from the block holder in a refrigerator, or by mechanical shock.

Before the lens components are cemented to the hard block holders, the holders are heated to 60°C or 70°C on a gas flame or in an oven. The holder is then loaded with individual wafers and reheated lens components, each one being pressed firmly into position as centrally as possible on its pellet.

Operation 12: Milling lens components on hard block holders

The process of rough grinding with loose abrasives is slow and expensive, and if the economic advantages bestowed by using hard block holders are to be fully exploited this process must be replaced by milling with diamond impregnated tools. Although we are introducing this process in the context of hard block holders it is, of course, of more general application, and in particular, it may be used for the preparation of lens blanks prior to smooth grinding and polishing in the pitch pellet method of glass processing.

The diamond tools used for this process consist of a steel or brass cup-shaped body and shank, the edge of the cup being provided with a copper lip, impregnated with diamond powder. This lip is generally convex in section to allow milling work to be performed on convex, concave and flat surfaces as shown in figures 2.17–2.19.

The adjustment of the position and inclination of the milling tool is achieved with the help of a dummy block of the appropriate radius. The edge of the cup-shaped tool must pass through the centre line of the workpiece at the precise point on the lip that is in contact with the surface being worked. The value of the inclination of the milling cutter, a, is given by the equation

$$a = \sin^{-1}(r_t/r_s)$$

where r_t is the radius of the contact circle at the edge of the cup tool, and r_s is the radius of the surface.

Figure 2.20 shows the same geometry applied in the situation where individual lenses are to be milled.

The use of the dummy block to set the angle of the milling head involves mounting it on the work spindle of the machine, located in the same way as the block to be processed, and with the dimension h of figures 2.17–2.19 reproduced

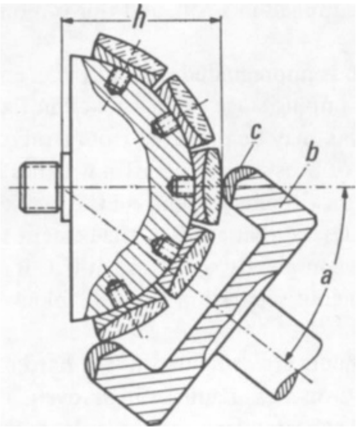


Figure 2.17 Milling a convex block. *h* Height to be maintained at a constant value for all blocks, *a* angle of inclination of the tool, *b* body of the diamond milling tool, *c* diamond impregnated cutting edge

to the required precision. The milling tool is adjusted until all points on its rim make contact with the dummy block, and the required intersection between that line of contact and the centre line of the machine is achieved. When the diamond tool is rotated by hand it should mark the dummy block appropriately. A trial cut is then taken with the machine on the first block, and this block is checked for edge contact in the fine grinding tool. If the machine is properly adjusted the block will rotate in the fine grinding tool with some resistance, but will not spin too freely nor be gripped too tightly by the tool.

A further guide to the correct adjustment of the milling cutter is the state of the witness marks.

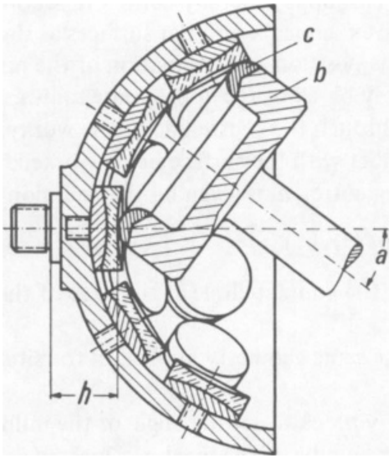


Figure 2.18 Milling a concave block, annotation as figure 2.17

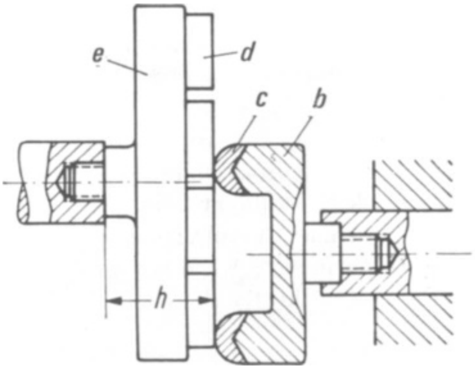


Figure 2.19 Milling a plane block, annotation as figure 2.17 except that $a = 0°$, e is block holder, d is plane glass components

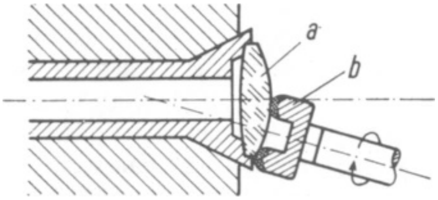


Figure 2.20 Milling a single lens component. *a* Lens clamped or held in a collet by vacuum, *b* diamond milling tool

Assuming a satisfactory adjustment has been achieved, the work may proceed on the complete set of blocks, each block being worked to the same stop setting.

After completion, the milled blocks should be cleansed of the mineral oil that was used as a cutting fluid, because this would otherwise inhibit the action of the abrasives that are used afterwards. A convenient method for this cleaning is to lay the blocks in sawdust and then blow this off with compressed air.

The milling of single lenses and blocks of lenses on hard block holders in mass production

Where the milling process is carefully tuned, lenses may often proceed directly to polishing from the milling stage, remaining on their hard block holders. In this situation, and also when there is further fine grinding to be performed, the state of adjustment and wear of the diamond tool must both be carefully monitored, and fine adjustments made as necessary.

For this reason, and because the milling process is not much like any traditional glassworking processes, it is usually convenient and economic to employ a machine setting technician, so freeing the machine operator to work as many machines as possible. The number of machines worked by any one operator strongly influences the profitability of the manufacturing process, and in even relatively simple optical systems there is considerable potential for increasing the number of machines operated by any one operator. For example, in the case of a simple four-component photographic objective of the Tessar type, one man, a setter and eight machines could keep a polishing workshop supplied with blocks ready for polishing, assuming that the blocked lenses pass directly from milling to polishing.

The individual process cycle times also influence the way the operator can share his time between different machines. A typical, medium-sized block may take approximately 3.5 minutes to complete, whereas a small, short-radius block may take considerably less time, so making the rhythm of the milling workshop more difficult to tune.

Operation 13: Grinding lenses on hard block holders

After milling, the blocks of lens components can be smooth ground in the same way as has been described in chapter 1 (tables 1.2 and 1.3).

The control of the precise radius of the grinding tool or tools at each stage is accomplished by reference to a master optical surface which may be a finished lens component or an optical test plate. If an optical test plate is used it should be segregated for grinding work because it will become scratched and rendered unsuitable for use on polished surfaces. The comparison between the master surface and the ground workpieces is made with a simple spherocomparator consisting of a steel cup, fitted with a micrometic dial gauge.

The quality of the ground surface finish is, of course, of great importance to the polisher, and great care should be taken to achieve the necessary uniformity and fineness of texture, while also reaching the required surface curvature at the same moment in the process. The requirements are of course identical to those described in chapter 1.

The radius of curvature of the successive grinding tools will change with wear, and it is necessary to rough polish a sample block at regular intervals to make sure that the sequence of grinding operations is appropriately tuned and adjusted to produce blocks that can be polished quickly and efficiently. The radius of such sample blocks should, of course, be checked by optical interference using an optical test plate.

Another condition must also be met, that is, that the centre thicknesses of the components are correct. This requirement is particularly strict for the second side processing and depends not only on the tuning of the process sequences but more particularly on the metrological quality of the machining and the cleanliness of the block holder and pellets. This thickness control may be monitored with a dial indicator as shown in figure 2.21, with the central probe acting as a depth gauge. For this control method to work it is of course necessary for the radius of curvature of the block holders to be held to a very tight tolerance.

Depending on the quantity of work, its rate of flow and the centre thickness

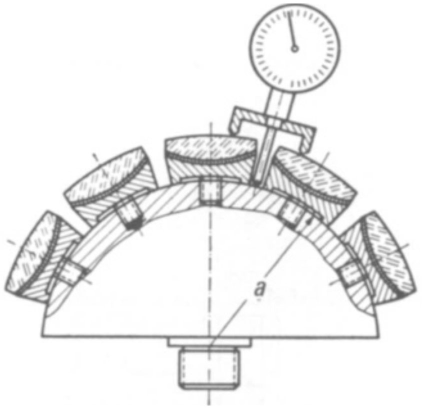


Figure 2.21 Monitoring centre thickness by depth measurement. *a* Base block holder radius which acts as the reference dimension

tolerances involved, so the centre thickness of the components can be controlled in this way and/or by the observation of witness marks.

Automation of the grinding process

Traditionally, the glass worker controlled each stage of the smooth grinding process, paying detailed attention to the progress of the surface texture and the centre thickness of the components. With the requirement for mass production has come the necessity for the planning and standardisation of each step in the process, and whereas the optical glass worker would have fed the loose abrasives by hand, standardisation of the process is best achieved, as in polishing, by a continual feed of a slurry of abrasive and water, mixed with a chemical suspension agent to inhibit the deposition of the abrasive grains during the cycling of the mixture. The arrangement of the machine to do this work is shown in figure 2.22, with the bowl of the machine attached to the spindle so that it rotates with the spindle and forms a seal. Slurry is confined to the working area, and thrown to the outside of the bowl, where it is picked up and pumped back on to the block.

A further degree of automation may be achieved by standardising the abrasive slurry and running each block for a standard time. This technique can be controlled by automatic timers and so the glass worker may operate more spindles and so improve productivity.

With due regard to the layout of the machines and the preparation of the blocks and so on, the limiting factor in maximising production rates emerges as the control and correction of the wear of the grinding tools. The best way of achieving this control depends on two factors: first, the milling process should be adjusted so that the minimum of fine grinding is necessary and second, the stroke of the machine should be adjusted so that the centre and edge of the block spend equal periods of time in contact with the grinding surface, or such deviation from this principle as

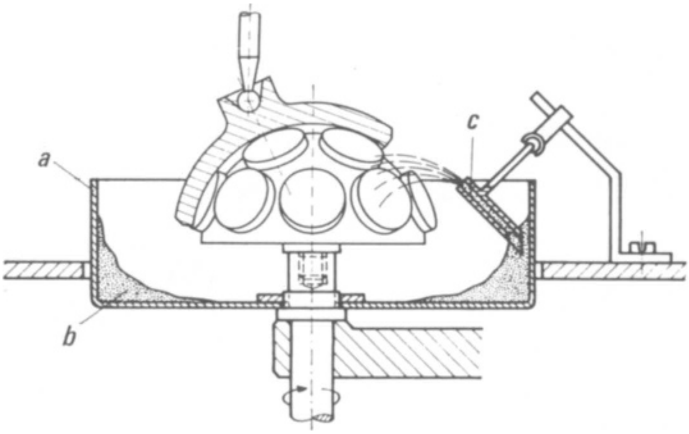


Figure 2.22 Rotating bowl for the automatic feed of abrasive slurry. *a* Rotating bowl, *b* abrasive slurry spun out to the edge of the bowl, *c* spraying tube.

the operator deems necessary to maintain the tuning of the process sequence and minimise the adjustment of the grinding tools.

The abrasive slurry and working technique used in this semi-automated process is different from that used in the traditional hand-fed smooth grinding. The hand-fed process uses a series of separate charges of abrasive, each of which is carefully controlled for dampness and quantity so that it may be 'worked out' to the stage where the abrasive particles are systematically broken down to a smaller size and held between the glass and the grinding tool by the surface tension and viscosity of the slurry. The skilled glassworker takes pride in the careful control of this process and the fine-ground scratch-free surfaces that can be produced. For the continuous feed of slurry, the machine should be supplied with enough abrasive to serve for several days, and the 'breaking down' process is no longer relied upon, so the size of the abrasive particles must be smaller, and the process time is usually longer.

Operation 14: Polishing lens components on hard block holders

The methods and machine adjustment described in chapter 1 apply unmodified to the polishing of lenses held on hard block holders.

The requirements of productivity dictate that as many spindles as possible should be superintended by each polishing worker and for this purpose the layout of the spindles should be as compact as possible, to avoid unnecessary movements of the polishing craftsman. The lower limit of spacing of the spindles is determined by the diameter of the bowl around the polishing spindle, and this means that the bowl should be as small as possible to allow the closest packing of the spindles.

There are two basic types of polishing machine mechanism: the traditional lever-arm pattern, and the swinging-arm variety. Either of these types may be assembled into rows, racks (see figures 2.23–2.26) or even in a circle around the operator. With an optimum arrangement it can be possible for a single polishing worker to superintend up to 36 spindles. If the full potential of such a production situation is to be achieved it is necessary that the number of spindles operated be chosen so that the sum total of time spent attending all the spindles is equal to the process cycle time of each of the individual blocks.

The work to be attended to at each spindle is as follows. The block is cleaned under luke-warm water to remove any particles of abrasive and bring the block holder up to the operating temperature. The block is then screwed on to the spindle and the polisher, with polishing medium, is placed on top, after having been warmed under warm water. The driving pin of the machine is then engaged in the polisher and the machine is started.

The ideal rhythm of work is then that each block is stopped at least once for its curvature to be checked with an optical test plate, its state of polish to be examined

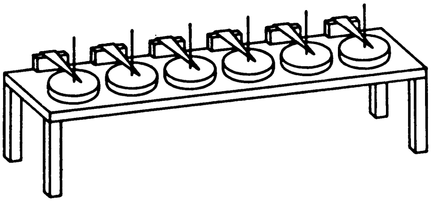


Figure 2.23 Spindles of lever-arm polishing machine arranged in rows

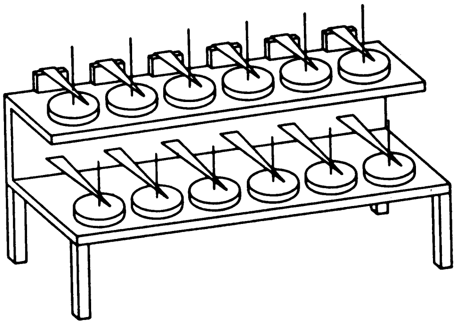


Figure 2.24 Spindles of lever-arm polishing machine arranged in racks

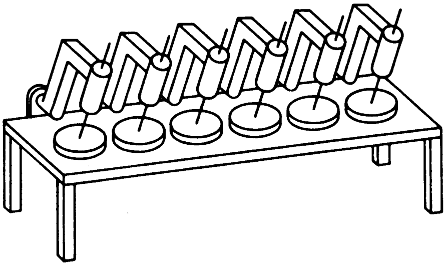


Figure 2.25 Spindles of swinging-arm polishing machine arranged in rows

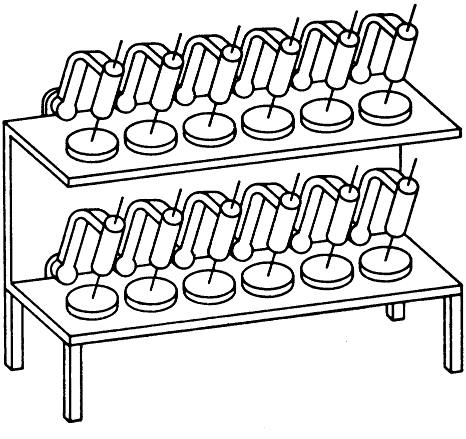


Figure 2.26 Spindles of swinging-arm polishing machine arranged in racks

and also for the centre of the polisher to be cut out and the irrigation channels cleared. By the time that this has been completed for each of the spindles, the first block should have finished its cycle and reached a final polish at the right radius and quality of surface shape. This is checked and the next block should then be completed and ready for final inspection.

When a block is completed it is examined with a X6 magnifier to ensure that it is fully polished and free from cosmetic blemishes, and then lacquered to protect the surface before being passed on to the deblocking process.

Such an ideal rhythm is not easy to achieve and it requires the full cooperation of the craftsmen and supervisors to work well, but if the large investment in hard tooling is to be justified such an ideal must be aimed at and achieved.

The achievement of a happy compromise of working patterns in the glass workshops should be the aim of the supervisors, management and craftsmen. Each craftsman will have his own preferred rhythm and style of work and it is the responsibility of the supervisor to fit each personality into the overall pattern of the work as happily and profitably as possible. This procedure will usually involve securing a suitable level of financial reward for cooperation and flexibility.

Polishers and polishing media

Traditionally, pitch and iron oxide rouge were the materials used in polishing, but there are now available on the market better and cleaner polishing powders and polisher mediums which offer considerable advantages.

Cerium oxide is now the most widely used rouge, and zirconium compounds can produce white polishing powders. These polishing powders ‘bite’ better and produce a polish faster, and are cleaner to work with than iron oxide rouge.

Polyurethane is also now widely used instead of pitch, and it is supplied in sheets of a controlled thickness which can be cut into circular, sectored polishing wafers and stuck to a carefully prepared tool with modern resin adhesives, using a forming tool of precisely the correct radius in the same way that a pitch polisher is formed.

Polyurethane foil polishers prepared in this way have produced a revolution in the polishing process. Their great advantage is that they retain their form for long periods and allow remarkable increases in productivity in the hands of even relatively inexperienced craftsmen when the full freedom for increased polishing pressure and speed is utilised.

Operation 15: Protective lacquering and deblocking

When the first side polishing is complete the block is lacquered to avoid oxidation or water stains and the block is placed in a refrigerator to detach the lens components from their metal seatings.

The hard block holders then have to be cleaned with particular attention to the precision lens seatings, and reloaded with fresh mouldings.

Operation 16: Milling or grinding to the required centre thickness

Depending on the tolerances specified for centre thickness, so different forms of lens component have to be processed in different ways so that mass production output can be achieved in the most economic fashion.

In the previously described process where the lens blanks are initially processed to flat plates or discs, the intrinsic accuracy of the flat milling process allows tight tolerances on the final thickness to be achieved, especially where both surfaces are convex. If in addition, the flat lens blanks are rough polished prior to spherical processing, the full potential for accuracy can be achieved and a final tolerance of ±0.030 mm is possible. Where the surfaces to be processed are concave, similar accuracies can be achieved if the discs are pre-edged to a precise diameter and the flat witness ring at the edge of the lens components is watched.

Where milled witness marks are used, a tolerance of ±0.100 mm is easily achieved without the necessity for the pre-edging of the blanks. Similarly, if a ring type of depth gauge is used, thickness tolerances of ±0.100 mm can be achieved.

For convex–concave lens components, achieving a centre thickness tolerance of ±0.03 mm is difficult in mass production on hard block holders, unless the diameters of the blanks are controlled to a precise value by pre-edging. If this is done, and the pellets are controlled to the same diameter, the blanks may be aligned on their pellets and the thickness controlled by reference to a ring contact at the edge of the pellets (see figure 2.27). For the tolerance of ±0.030 mm to be achieved care must be taken to clean the lens seatings and also to work the surface curvature of the base tool to a precise value so that its surface may be used as a datum for depth measurement (figure 2.21).

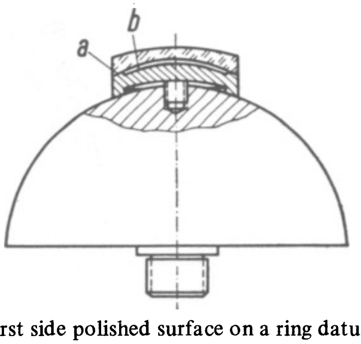


Figure 2.27 Location of the first side polished surface on a ring datum. *a* Peripheral datum, *b* undercut surface

Operation 17: Unblocking and reblocking of lenses on hard block holders

The unblocking of lens components can be accomplished by placing the finish-polished blocks in a refrigerator. Alternatively, if the block holders are required for more or less immediate re-use, then heating the block holders can serve the double purpose of loosening the completed components and heating the block holder for the next charge of lenses.

When the block is heated for the purpose of attaching new lens components, care must be taken to raise the block to just the right temperature. If the block holder is raised to too high a temperature the lens component will slide about too much and there will be the risk of damage. At just the right temperature it will be possible to remove any traces of wax from the seatings easily and then press the new preheated lens components into position on fresh wax cement wafers. This operation is usually aided by the use of a wooden handle supplied with a felt-lined cup; this tool will allow the operator to apply more pressure and achieve a uniformly thin cement film (figure 2.28).

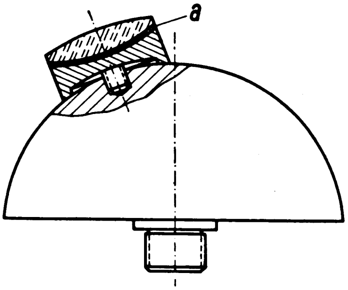


Figure 2.28 Spot-face lens holder without retaining rim. *a* Cement wafer

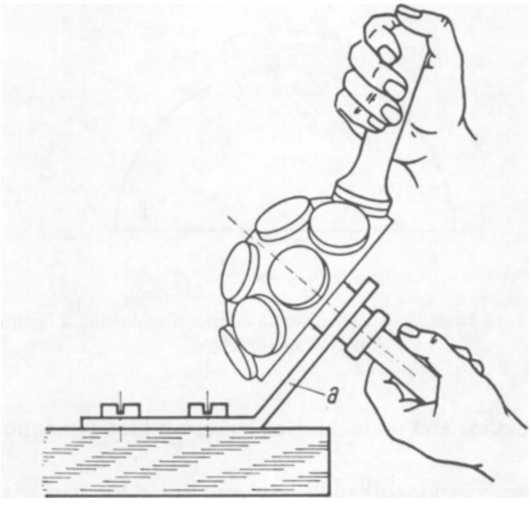


Figure 2.29 Inclined support of block during cementing. *a* Inclined support bracket with V location slot

The slipping of the lenses occurs because the button supports are not provided with any retaining rim, and the effect will be particularly pronounced if the temperature of the block holder is not correct. This is particularly a problem where the block is hemispherical, and in this case the block holders are normally held in an inclined position as shown in figure 2.29. The block is rotated by hand during the loading process and in this way the tendency for the lens components to slide is counteracted by the constantly changing attitude of the seatings.

Operations 18, 19, 20 and 21: Second side processing

These operations are described under operations 12 to 15 of this chapter. The quantitative details of cement types, operating radii, and so on, depend, of course, on each specific job.

Operations 22–28: Finishing operations

These operations are described under operations 12 to 17 and 19 in chapter 1.

3

Manufacture of Binocular and Telescope Lenses

Although the general principles of processing glass for the lenses of binoculars and telescopes are the same as for photographic lenses, the radii of curvature of the surfaces of the objectives are usually longer, and the apertures larger, so it is more economic to increase the diameter of the blocks.

For small batch sizes the pitch-pellet sticking method may be used, although in the case of the larger objective components, care must be taken to avoid straining them such that their surfaces assume a different shape when they are deblocked. The origin of this straining problem lies in the thickness to diameter ratio which will often be unsuitable for easy surface shape control.

The tolerance on thicknesses is usually large enough to allow the use of the witness-mark method of thickness control, or other less direct methods.

The inspection of completed telescope objectives can often be most easily achieved by providing a master telescope whose quality has been measured, and then replacing its objective by each production objective in turn, and observing the image quality.

Inspection of telescope objectives for resolving power

When used under carefully controlled conditions the visual resolving power of a telescope objective is an appropriate indicator of manufactured quality. The telescope may be set up to view a series of grating objects of varying spatial frequency at strategic points in the field of view, care being taken to ensure that there is adequate magnification to avoid resolution effects in the observer's eye. This last condition may be achieved by providing the observer with a viewing telescope with which to look through the telescope under test. This viewing telescope may be provided with dioptric calibration, so that the relative focal power of the telescope at different points in its field of view may also be measured.

It is usual to provide a collimator with the resolution targets in its focal plane, to avoid the need for targets to be placed at an inconveniently large distance away from the observer. The focal length of this collimator should be at least three times that of the objective under test, to avoid the aberrational effects of the collimator itself.

The test target will normally be of the form shown enlarged in figure 3.1, with black lines spaced by their own thickness. This example is intended for use without a collimator for a X8 telescope and to be placed at 10 m from the objective under test, when the spatial wavelength should correspond to 7.5 seconds of arc or 480 cycles/degree. The patterns will be provided in pairs, one set of lines being disposed vertically and the other set horizontally or radially and tangentially if they are positioned in the field of view away from the axial point. The provision of two targets perpendicular to each other allows the observer to detect any astigmatism.

The recorded resolution is identified by observing a number of these targets of different spatial frequency and selecting the pattern that is only just recognisable as a grating of separate lines.

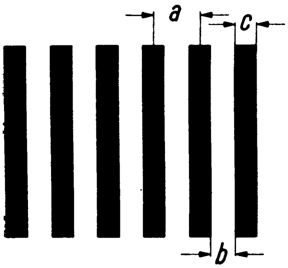


Figure 3.1 Dimensions of a resolution test chart suitable for an 8 x 30 telescope, to be placed at 10 m. *a* Pitch = 0.36 mm or 7.5 angular seconds, *b* gap between lines = 0.18 mm, *c* line thickness = 0.18 mm

The resolution of the human eye is approximately 1 minute of arc, or 60 cycles/degree, and when the exit pupil of the telescope is larger than the pupil of the observer's eye, as is usually the case with hand-held telescopes and binoculars, we may expect to be able to resolve:

$$\text{angular telescopic visual resolution} = \frac{\text{visual acuity of the eye}}{\text{telescope magnification}}$$

Thus, for an X8 hand-held telescope we should be able to resolve 1 minute of arc ÷ 8 = 7.5 seconds of arc, that is, 0.0000364 radians, so that a test target such as that shown in figure 3.1, placed at 10 m from the telescope should be reproduced with the line separations at 10 m x 0.0000364, that is

$$10 \text{ m} \times 0.0000364 = 0.364 \text{ mm}$$

However, such a viewing arrangement may not test the full aperture of the telescope because the observer's eye pupil selects only a sample aperture from the instrument pupil. When an appropriate viewing telescope is provided, the final instrument pupil may be made smaller than the observer's eye pupil and the defects of the viewing telescope and the observer's eye can be ignored. Under these circumstances the full aperture resolving power of the telescope is given by the approximate formula

$$\text{angular resolution for standard bar charts} = \frac{2\lambda}{D} \text{ radians}$$

where λ is the wavelength of light, which may be taken as 0.55 microns for a visual system, and D is the diameter of the aperture of the telescope.

Normally, a manufacturing acceptance specification would not demand that the telescope should resolve to the full theoretical resolution limit, and in any case such a specification should pay due regard to the performance of the instrument off axis, which will not in any case be as good as in the central part of the field of view. The design engineer and the test department are responsible for drafting a manufacturing acceptance specification that will ensure that the instrument will pass the user's specification. Such a manufacturing acceptance specification may be best expressed in terms of the tolerable dioptric settings of the viewing telescope when the resolution or contrast at the field point under consideration is maximised. This leads to the concept of the focal surfaces of the visual field as viewed through the telescope, resulting from field curvature, and astigmatic aberrations.

As in all optical testing work, precautions must be taken to standardise and control the observing conditions, so that, for example, the illumination level and colour of the lighting are known and adjustable to standard values. Similarly, precautions must be taken to ensure that the observer's visual performance is of an acceptable standard, by whatever objective tests as may be necessary.

4

Manufacture of Microscope Lenses (6 different process descriptions, according to the form of the lenses)

With the exception of some lens components required for surgical endoscopes the lens components used in microscope objectives are the smallest generally encountered in the optical industry.

The components used in microscope eyepieces are no different, from the processing point of view, from most components found in photographic systems or telescope eyepieces and are not dealt with separately here.

The components for high-power microscope objectives are however characterised by small diameters, steep surface curvatures and tight centre thickness tolerances. These characteristics lead to the need for special methods of manufacture.

The special categories of components that can be identified are as follows:

(1) Components that for production engineering reasons are to be edged prior to smooth grinding and polishing; with either shallow curvatures and meniscus form, with centre thickness tolerance ±0.005 mm, or hemispherical form, centre thickness tolerance ±0.01 mm.
(2) Lenses that reduce to being sharp edged and that need not be centred on edging machines.
(3) Lenses that have to be polished as single surfaces on both sides.
(4) Lenses that can be polished on a block for the first side, but that must be worked individually on the second side.
(5) Lenses that are to be polished as single surfaces on the first side and on a block for the second side.
(6) Objective front components, which in quantity production are manufactured out of glass spheres.

There now follows a detailed description of the manufacture of a representative example of each of the above categories.

The raw material in each case will normally be prepared as cylindrical discs; where mouldings may be used the work is the same as described in chapter 1.

Because of the steep surface curvatures involved in microscope objectives, many are made on small foot-driven treadle machines or on motor-driven single-spindle machines, which may be either horizontal or vertical.

The lens components are cemented to wooden or metallic pegs or handles and worked in the grinding and polishing shells with the usual systematically irregular motion. The grinding and polishing shells are, of course, much smaller than those found in the case of photographic or telescope objectives.

For mass production, the hand work involved in grinding and polishing individual components has largely been replaced by specially designed machines such as that shown in figure 4.1, which simulate the manual techniques.

The swinging arm of the machine carries a motor driven spindle which, in addition to its own rotation, also drives the engaging poker pin shown at *c* in a planetary fashion. The connecting rod *k* drives the swinging arm to an extent that is dependent on the stroke adjustment in such a way as to impart an asymmetric

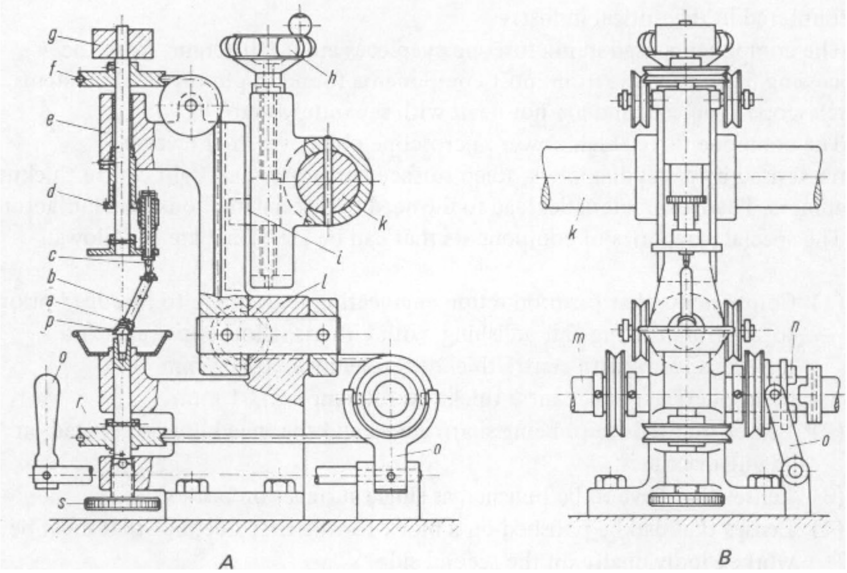


Figure 4.1 Processing machine for microscope lenses: (A) side view, (B) front view. *a* Lens, *b* lens handle or peg, *c* machine engagement pin, *d* planetary drive, *e* swinging arm, *f* belt for upper drive, *g* weight for polishing force, *h* adjustment for the swing angle, *i* engaging trunion, *k* connecting rod, *l* bearing for the swinging arm, *m* machine drive, *n* coupling for starting spindle, *o* gear lever for the coupling, *p* polishing shell, *q* lower drive, *s* height adjustment for the lower spindle

movement to the lens component through the peg *b*, so simulating the motion of the optician's hand manipulations.

The spindle that carries and drives the polishing or grinding shell is located at the bottom of the machine and it may be adjusted for height while its direction of rotation is opposite to that of the swinging spindle.

This machine is sufficiently small that an operator can sit and operate at least six of them if they are arranged in a suitably ergonomic fashion.

The machine pegs that have the lens components cemented to them are usually metal and they must be provided with a hole and a slit so that they may be engaged with the spherical end of the machine-drive pin when they are in an inclined position.

Certain peculiarities of the administration of the work should be noted. Generally, all the glass-processing operations for microscope lenses will be done by the same worker. This is particularly necessary where components have to be worked to very fine tolerances on centre thickness, so that compensating action may be taken at each stage without burdensome paperwork. For the same reasons the components should not generally be moved between departments for different processes, and as far as possible should be stored in the close vicinity of the work area. The flow of the work will generally be well known by the craftsmen in the microscope lens department because of their individual involvement with each process, and for this reason it is not usual to supply planning layouts or detailed process instructions for the manufacture of components that involve such high levels of skill.

(1) Microscope lenses that may be, or have to be, edged before polishing

As a general rule in manufacturing, the most sensitive surfaces will be processed last of all, to avoid cosmetic blemishes, but in optical work this is not usually the preferred order of working, because the edging process corrects the centration of the lens components. In the case of steeply curved lens components, however, it is possible to edge prior to polishing because the basic centration of the component will have a higher degree of stability than lenses with shallow curvatures. This advantage is particularly strong for hemispherical components, where the centration is maintained automatically.

In the case of meniscus components with very low optical power it is necessary to edge prior to polishing in order to improve the centration of the finished component, because it is usually possible to mill with the necessary truth more easily than it is to grind with loose abrasives, and the edging process cannot in any case restore the centration of such a component after polishing.

Two examples of typical lens components will now be considered.

Example 1. Consider a convex–concave meniscus as shown in figure 4.2. For such a lens component it is not appropriate to use lens mouldings, and the raw material

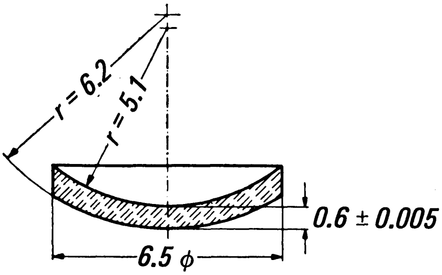


Figure 4.2 Example of a convex–concave meniscus lens

will consist of cylindrical blanks of 8.5 mm diameter x 3.5 mm ± 0.1 mm thick. The processes involved in the manufacture of these blanks is described in chapter 1.

In order to achieve the final centre thickness tolerance, the diameter should be controlled to within ±0.01 mm and the first side initial curvature applied by hand after the disc has been cemented on its peg (figure 4.3). It is necessary to apply this curvature by hand to ensure that it is concentric with the edge, eccentric manual pressure being applied during grinding to achieve the required concentricity. The grinding is continued until there is a sharp edge formed all around the blank at the same time. In the case of the component shown in figure 4.2 the radius applied would be 5 mm, so that the surface bites the edge of the polisher and the polish starts at the edge and works in towards the centre in the fashion necessary for stability and the smooth progression of the polishing.

When the final 5.1 mm radius is polished the components are removed from their pegs and cemented with their polished side down on a flat tool, as shown

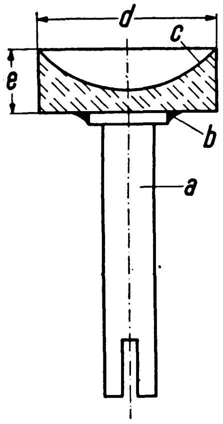


Figure 4.3 First side working of the lens component shown in figure 4.2. *a* Machine peg, *b* cement, *c* radius ground with sharp edge, *d* diameter including allowance of ± 0.005 mm, *e* thickness of initial blank

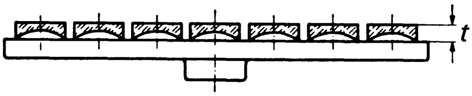


Figure 4.4 Grinding of the lens components to a uniform thickness. *t* Thickness controlled to a tolerance of ± 0.005 mm, using depth measurements at several places on the block to achieve this

in figure 4.4, and then ground and rough polished flat to their finished thickness + 0.01 mm, so that the flat surface can be used as a witness mark for the grinding of the second side.

The grinding and polishing of the second side may now proceed after the component has been cemented on to a true mandrel and centred so that its edge runs true as shown in figure 4.5. The centration of the mandrel is adjusted with the aid of a dial indicator as shown in figure 4.5 using the eight adjusting screws shown there.

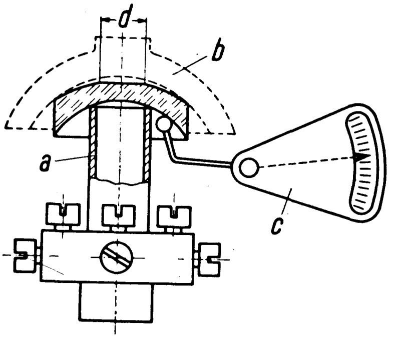


Figure 4.5 Roughing the second side of the lens. *a* Eight screw adjustable mandrel (as shown) or true chuck, *b* diamond grinding shell, *c* dial indicator, *d* 3 mm diameter witness mark

The next operation is to apply the curvature shown in figure 4.5, leaving a witness diameter of 3 mm to aid the final thickness control. This curvature should be true to the first surface and may be checked for this with a dial indicator just as the blank was checked for centration when it was cemented to the mandrel. Depending on the equipment available in the workshop, it may be more convenient to apply a conical chamfer rather than a curvature to this surface. As long as the subsequent curvature locates on the outer diameter of the chamfer this is quite acceptable.

After this truing–roughing operation the components are decemented from their mandrels and attached to pegs for smooth grinding and polishing, as shown in figure 4.6. This part of the work is normally done by hand and the central witness mark reduced to 0.1 mm diameter at the rough-polished stage, when the components are again removed and edged to their finished diameter of 6.5 mm, with appropriate gauging and chamfers applied as required. Finally, the second side is finish polished until the witness mark just disappears and the surface achieves a suitable degree of

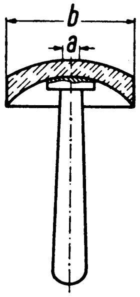


Figure 4.6 Lens component to be finish polished. *a* Witness mark at 0.1 mm diameter, *b* finished diameter

polish and adequate surface shape, as measured by the appropriate test plate. At this stage the finished thickness tolerance of ±0.005 mm should have been achieved.

Usually in the case of microscope lenses a very high standard of surface form must be maintained, and also a high standard of cosmetic quality, and for this reason an independent inspection is necessary

Example 2. Consider the component shown in figure 4.7, and it will be seen that the convex surface is hyper-hemispherical, and the concave surface is nearly hemispherical.

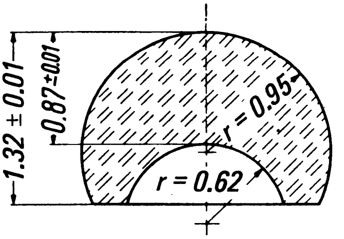


Figure 4.7 Working drawing for the hemispherical lens example

For the manufacture of such a lens, the lens blanks should be 2.5 mm diameter and 2.0 mm thick (figure 4.8). The concave radius is first ground in the blank by hand, using a datum centre hole machined with a diamond drill (as shown in figure 4.9) to achieve centration between the concave surface and the cylindrical edge.

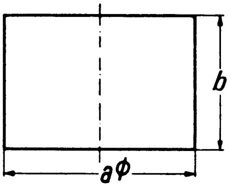


Figure 4.8 Lens blank, *a* Diameter = 2.5 mm, *b* thickness = 2.0 mm

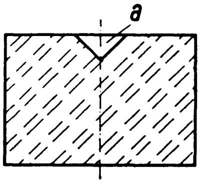


Figure 4.9 Centre drilling. *a* Preliminary centre made with a diamond drill

The concave surface should be ground deeper than hemispherical by approximately 0.15 mm as shown in figure 4.10, so that for subsequent centration there is enough material on the flat face to remove the errors of truth.

The next operation is to finish polish the concave surface using the machine shown in figure 4.1.

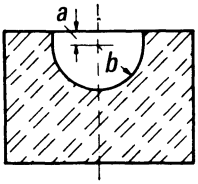


Figure 4.10 Polishing the concave side. *a* Centre depth, *b* final surface radius

As with the previous example the flat second side is now smoothed and rough polished so that the centre thickness is the final value + 0.02 mm, the flat surface being to provide witness marks for centre thickness control (figure 4.11).

For the grinding of the convex side, the lens component is mounted so that its concave surface is running true and then its convex surface is milled with the special-purpose machine shown in figure 4.12

The special grinding machine shown in figure 4.12 is provided with a spherically polished mandrel held true in its collet, to which the lens component is cemented with clean cement. The mandrel may be adjusted in the collet to achieve centration before the lens component is cemented to it.

The rotating diamond lap is next brought to the lens component, and by swinging the circular support the hyper-hemisphere is generated at a radius to

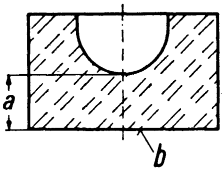


Figure 4.11 Flat surface ground and rough polished to the finished thickness plus allowance. *a* Finished thickness plus allowance, *b* rough polished flat surface

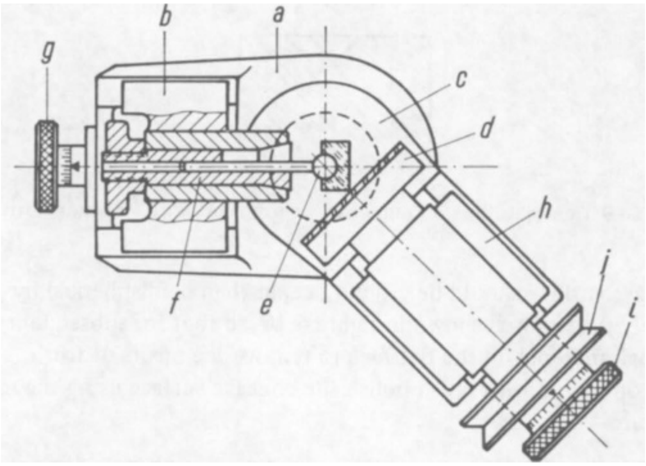


Figure 4.12 Milling machine for the initial milling of the second side of the lens. *a* Machine support table, *b* slide for the adjustment of the centre, *c* circular support, *d* diamond tool, *e* spherical headed stud, *f* collet, *g* adjustment control for centration of stud, *h* machining slides, *i* diamond tool adjustment control, *j* drive pulley for diamond tool

achieve edge contact with the smooth grinding shell. When this process is complete the flat witness-mark diameter should be 0.5 mm.

The next operation is hand-held smooth grinding of the convex surface. This involves decementing the component from the machine mandrel and attaching it to a hand peg and then working it in the necessary smooth grinding tools until the witness patch has a diameter of 0.1 mm, when the surface may then be rough polished (figure 4.13).

The rough-polished component is next removed from the hand peg and mounted on an adjustable mandrel as shown in figure 4.14, and so adjusted that the two surfaces run true, when the flat may then be ground parallel to the datum shoulder of the mandrel.

As with the previous example the final operation is to finish polish the convex surface with the lens component held on a peg for hand manipulation. Careful

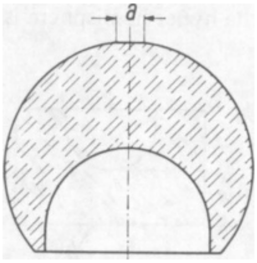


Figure 4.13 Second side of the lens ground and rough polished. *a* Diameter of the witness mark, approximately 0.1 mm

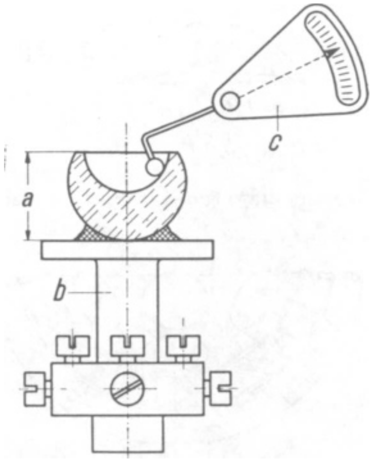


Figure 4.14 Milling to the finished height. *a* Finished height, *b* eight screw adaptor with flat cementing surface, *c* dial indicator

observation of the witness mark reveals when the component has reached the required thickness to within ±0.01 mm.

The utmost care must be exercised by the craftsman in finishing components of this type, and rectification of cosmetic and surface form errors after inspection must similarly be carried out with the utmost care, usually by the same craftsman who did the original work.

(2) Sharp-edged microscope lenses that do not require edging

There is no need to explain that in optical glassworking, sharp, unchamfered edges are to be avoided at all cost, but in the case of some high aperture microscope objectives it is not always possible to avoid convex components with sharp edges. To work such components it becomes necessary to cement the components to an auxiliary edge guard support which is worked along with the lens surfaces, and in this way sharp edges may be produced without chips.

The skill required to work these lenses in this way is unusually high, and the processes do not lend themselves well to mass production.

Two examples of these types of component will now be considered.

Example 1. This is shown in figure 4.15. The blanks required for this lens must have a diameter of 4.5 mm and a thickness of 1.8 mm.

As with most meniscus lenses the concave surface is finished first. In this example the concave radius is much longer than the diameter of the component and the first side processing can be completed on a block of 12 lenses in accordance with the methods described in chapter 1. The surface is finish polished to a sharp

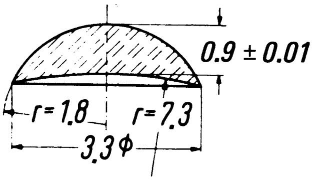


Figure 4.15 Working drawing of a sharp-edged meniscus lens

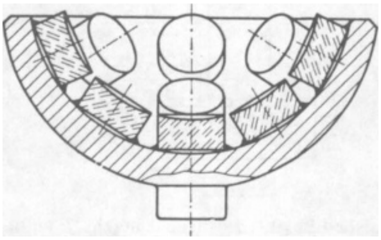


Figure 4.16 First side of the lens ground and polished on a block holder.

edge (figure 4.16) and the components are deblocked and cleaned in the normal way.

Before final grinding and polishing work commences on the second side, the lenses should all be ground to a uniform thickness, and to achieve this a short radius convex grinding tool is applied to the unworked surface, and a depression made until the centre thickness is 0.9 mm plus 0.02 mm allowance, as shown in figure 4.17. This convex witness depression should be rough polished. After this the components may be cemented to a flat tool and ground down to the required thickness, when the witness marks will be 0.1 mm diameter and still visible because of the polished finish in the witness mark. It is only necessary to mark three components in this way for each block of components, and they should, of course, be distributed uniformly around the edge of the block, as is shown schematically in figure 4.18.

The lenses are then deblocked and checked for centre thickness, prior to being cemented in place on their edge guard support which is to be worked along with the second side of the lens component (see figure 4.20). Notice that the support piece cum guard ring must be larger than the component that is being worked. The edge guard support pieces are used once only and must be made like a further lens component as shown in figure 4.19.

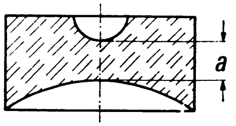


Figure 4.17 Lens component with witness mark cavity applied. *a* Finished thickness plus allowance

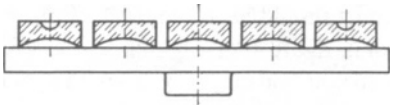


Figure 4.18 Grinding down to thickness and rough polishing

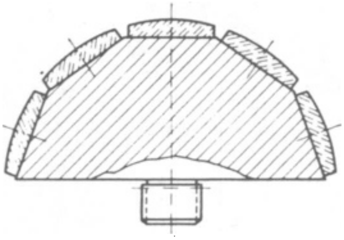


Figure 4.19 Block for grinding and polishing the auxiliary support pieces

The auxiliary guard ring support pieces may be made from plate glass and where large quantities are required they may be worked on hard block holders prepared in the usual way (figure 4.19).

The roughing of the convex second side may be completed with a machine of the type shown in figure 4.12, leaving a witness mark of diameter 0.5 mm, care being taken to ensure that each component is held in the machine so that the centre thickness is worked to the same value for each piece. The adjustment of each piece in the collet is done with the help of a hinged datum stop which is positioned with respect to the centre of the circular supporting table, but which can be set for different jobs. The mandrels with the lenses are shifted in and out and clamped when they are in contact with the datum stop.

After milling, the lenses are smooth ground and polished on a machine of the type shown in figure 4.1, until the witness mark has just been removed. At this

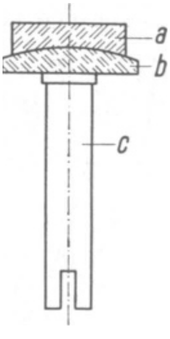


Figure 4.20 Lens and auxiliary support piece cemented on to machine peg. *a* Lens, *b* auxiliary glass, *c* machine peg

stage the lens centre thickness should be as required within ±0.01 mm and the workpiece will be as shown in figure 4.21.

Decementing the finished component from its auxiliary support requires the utmost care to avoid chipping the edge. Any chip introduced at this stage is likely to be large and will render the component useless.

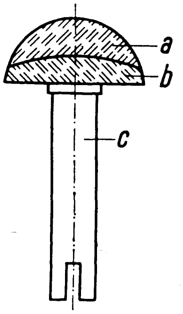


Figure 4.21 Completed component. *a* Finished lens, *b* auxiliary glass, *c* machine peg

The next operation is to apply the lightest possible edge chamfer to the component, as shown in figures 4.22 and 4.23. The mechanical edges of such components are not used as a datum in mounting and there is no stringent requirement for their truth, so this can be done by careful manipulation.

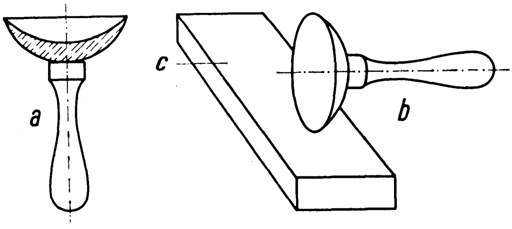


Figure 4.22 Chamfering the sharp edge of the lens by hand. *a* Lens on peg, *b* lens on peg being worked on oil stone, *c* oil stone

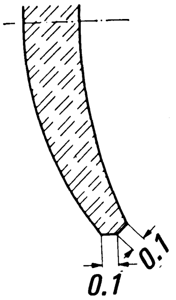


Figure 4.23 Final chamfer on the lens component

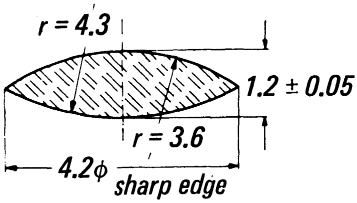


Figure 4.24 Working drawing of a sharp-edged biconvex lens

Example 2. We shall now consider the manufacture of a sharp-edged biconvex lens in which each surface has to be worked singly. This component is shown in figure 4.24.

The glass blank size for this lens should be 5.5 mm diameter x 1.7 mm thick.

Both sides of the component may be smoothed and polished on the microlens swinging-arm machine, and so the first operation is to cement the glass blanks to their machine pegs and rough out the first sides holding the machine pegs by hand (figure 4.25).

If one were to use a normal rough grinding shell to generate these curves it would take a long time, so it is better to use a micromilling machine of the type shown in figure 4.12. Alternatively, the initial roughing can usefully be completed on a disc tool with circular channels as shown in figure 4.26. This tool may

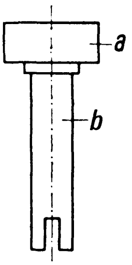


Figure 4.25 Component on machine peg. *a* Component, *b* machine peg

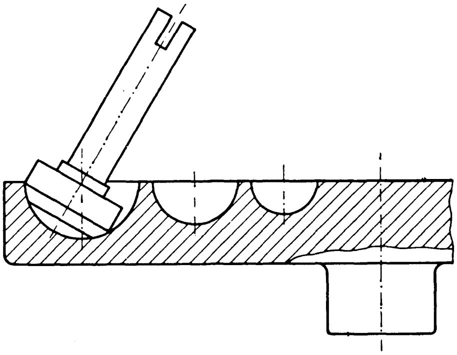


Figure 4.26 Initial roughing on a disc tool with circular channels

typically be 200 mm in diameter, with several grooves of different radii. On account of the outer grooves running at a higher peripheral velocity the speed of cutting is greater at the edge, and it is usual to work from the outer grooves towards the centre.

Fine grinding and polishing for the first side is completed in the usual fashion, using the microlens polishing machine shown in figure 4.1.

As before, the components are now deblocked and witness-marked with a rough-polished depression as shown in figure 4.27, to a centre thickness of 1.2 mm + 0.07 mm. Next they are ground so that the witness-mark diameter is reduced to 0.1 mm as shown in figure 4.28.

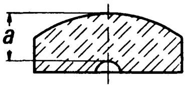


Figure 4.27 Witness mark ground in the component. *a* Finished centre thickness plus allowance

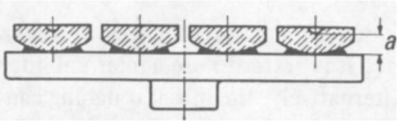


Figure 4.28 Components ground to thickness and rough polished

Next, the components are cemented to concave auxiliary support pieces to avoid edge chipping in subsequent processing (figures 4.29 and 4.30). It is usual in this process to prepare the auxiliary support pieces so that they make edge contact with the component that is to be worked; this provides extra stability to the component and achieves centration more readily.

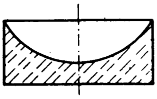


Figure 4.29 Auxiliary glass piece

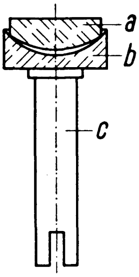


Figure 4.30 Lens and auxiliary glass piece cemented to machine peg. *a* Lens, *b* auxiliary glass piece, *c* machine peg

The initial roughing of the second side may also be achieved on a ring roughing tool as shown in figure 4.31 and the witness mark may be reduced to a diameter of 0.5 mm in this process before passing on to smooth grinding and polishing (figure 4.32) which is best performed on the microlens swinging-arm machine. As before, when the witness mark is just removed the component will have reached its required thickness.

Finally, the lenses are removed from their auxiliary glass pieces and lightly chamfered by hand as shown in figure 4.33, prior to final inspection.

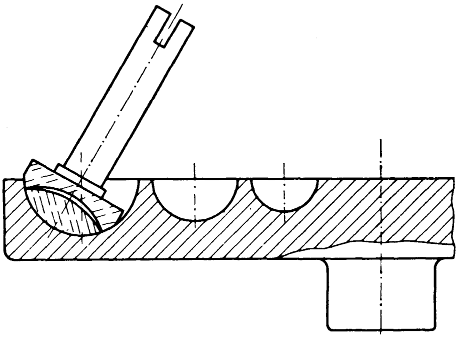


Figure 4.31 Initial rough grinding of the second side

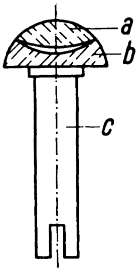


Figure 4.32 Final polished second side. *a* Finished lens, *b* auxiliary glass piece, *c* machine peg

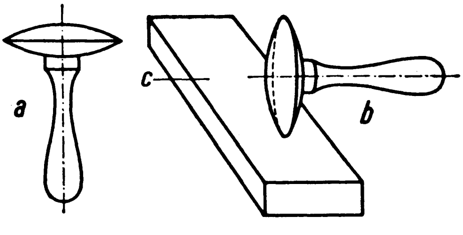


Figure 4.33 Removal of sharp edges by hand. *a* Lens on peg-wood, *b* lens being worked on the oil stone, *c* oil stone

(3) Microscope lenses where both sides must be individually worked

There are two reasons for working lens surfaces individually: (i) steep surface curvatures where it would be physically impossible to form a block of components, and (ii) tight centre thickness tolerances of the order of ±0.01 mm.

As an example we shall consider the biconcave component shown in figure 4.34. The glass blank required will be 6 mm in diameter and 3.2 mm thick.

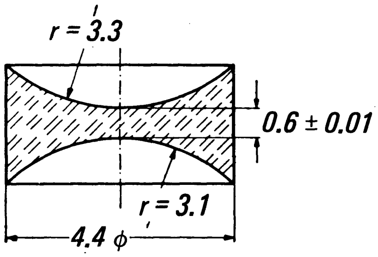


Figure 4.34 Working drawing for biconcave lens example

The first step is to stick the blanks to their machine pegs and grind and polish the first sides to the required depth, leaving an edge of width 0.2 mm (figure 4.35). The tolerance on curve depth should be ±0.01 mm. This stage may be completed using the microlens swing-arm machine.

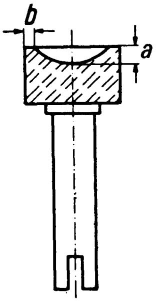


Figure 4.35 First side ground and polished to an accuracy of ± 0.01 on depth. *a* Depth (± 0.01 mm), *b* edge width 0.2 mm approximately

The components are next ground to a parallelism of ±0.005 mm, as shown in figure 4.36. This tight tolerance is necessary if the components are to achieve the final ±0.01 mm tolerance on centre thickness.

The second side involves careful hand working again, to achieve the required depth of curve ±0.01 mm, because there is no possibility of subsequent correction. If the flat working of these components is not entirely successful in hitting off the required edge thickness it is possible to calculate the required depth of curvature to

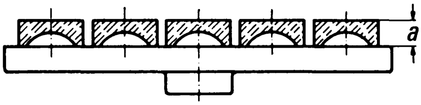


Figure 4.36 Grinding to the required edge thickness. *a* Uniform edge thickness ± 0.005 mm

compensate errors, from the formula

$$c = b - a - (d + 0.02 \text{ mm})$$

where the notation is explained in figure 4.37 and where the 0.02 mm is an allowance for polishing.

While polishing the components on the automatic microlens swinging-arm machine it is important to run each surface for a specific period, to achieve consistency of centre thickness. For this purpose it is necessary to run a trial batch of components to determine the required running time that will achieve an adequate polish and remove an appropriate thickness of material.

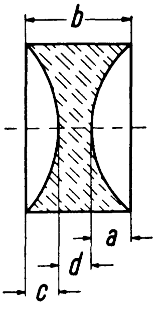


Figure 4.37 Centre thickness of the finished component depends on accurate working of each surface, and precise calculation of the second side working depth. *a* Depth of curvature for the first side, *b* edge thickness, *c* depth of curvature for the second side, *d* centre thickness

The final process is to remove the components from their machine pegs and edge them in the normal way as described in chapter 1.

(4) Microscope lenses whose first side may be processed on hard block holders, and whose second side is worked as a single surface

Single surface working offers the advantages of sensitivity in both surface shape and centre thickness control, but it should be avoided if at all possible for economic reasons, and either pellet blocking or hard blocking should be used as the preferred alternative.

As an example of a component where at least one surface can be processed using a hard block holder, we shall consider the lens shown in figure 4.38.

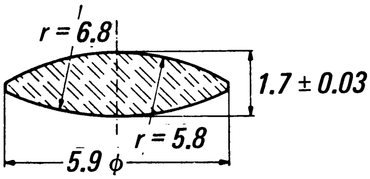


Figure 4.38 Working drawing for a biconvex lens

Although the component has an edge thickness, that edge thickness is sufficiently small that the component will become sharp edged when its second side is finish polished.

The raw material for this component will be 7 mm diameter x 2.6 mm thick.

The first side processing starts with blocking up groups of three components for the grinding and polishing of the 6.8 mm radius (figure 4.39). This radius is sufficiently long relative to the diameter of the component to enable blocks of three components to be formed, without approaching the hemispherical form too closely.

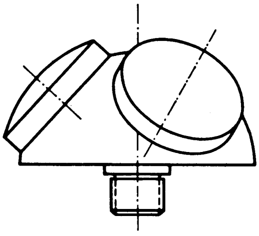


Figure 4.39 First side ground and polished in a block of three components

As the first side surface is worked with coarse and then fine abrasives, the centre of each component remains flat until the very last stage, so in this way the flat surface of the blank acts as a witness mark for the final stages of fine grinding.

The three lens blocks are next polished and the lenses removed from the block holders for cleaning and preparation for the second side processing.

Depending on the centre thickness tolerance, so one may now either apply witness marks (figure 4.40), or grind a plano block of components (figure 4.41) parallel to within fine limits as in the last example above.

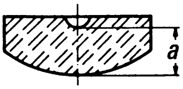


Figure 4.40 Witness-marked component ready for second side processing. *a* Finished thickness plus allowance

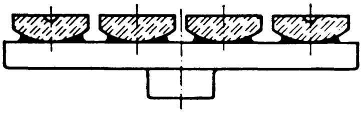


Figure 4.41 Grinding down to thickness and rough polishing

The processing of the witness-marked or plano and rough-polished second side now follows the stages already described for a biconvex lens under subsection (2) above. The layout of operations will be as follows:

(a) Stick lenses to auxiliary glass pieces (figure 4.42).
(b) Stick compound component to machine peg.
(c) Rough grind in the ring lap (figure 4.43).
(d) Grind and polish using the micro swinging-arm machine, taking guidance from the witness marks for thickness control (figure 4.44).
(e) Decement, clean and edge to the required diameter.

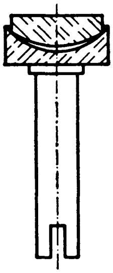


Figure 4.42 Lens and auxiliary glass piece stuck to machine peg

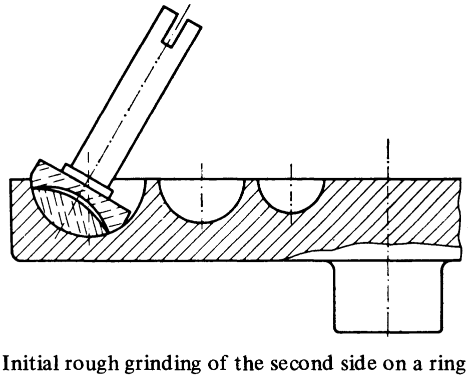


Figure 4.43 Initial rough grinding of the second side on a ring grooved lap

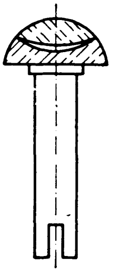


Figure 4.44 Second side of the lens finish polished

(5) Microscope lenses whose first sides are worked individually, and whose second sides are worked on hard block holders

In the case of negative meniscus lenses whose convex surface is shallow, the convex surface is worked last, with the components mounted on block holders.

Thickness control in this case may be achieved by the use of a dial gauge as shown in figure 4.45, and in this way the necessity for witness marking or plane parallel working is avoided.

For thickness control by dial gauge to be applicable, however, it is necessary to pre-edge the components so that the first side working produces a standard depth of curve. The pre-edging operation should work to a diameter tolerance of +0, –0.01 mm.

As an example of this type of lens we shall consider the component shown in figure 4.46.

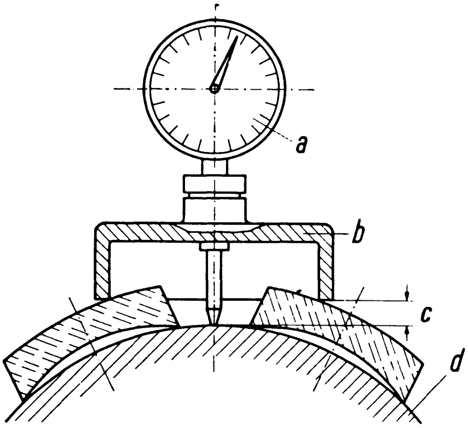


Figure 4.45 Depth measurement for thickness control. *a* Dial indicator, *b* measuring bell, *c* distance from the bell edge to the base datum, *d* block holder. The dial indicator must be set to a reference depth calibrated with slip gauges prior to this comparative measurement

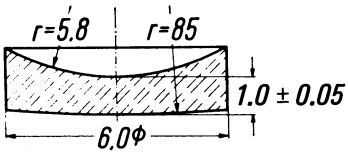


Figure 4.46 Working drawing of the concave meniscus component

The raw material size for this component should be 7.5 mm diameter x 2.1 mm thick.

The concave surface is ground by hand to produce a sharp edge, the workpiece being held on a machine peg for the operation, as shown in figure 4.47.

The fine grinding and polishing of the concave surface is completed using the machine shown in figure 4.1.

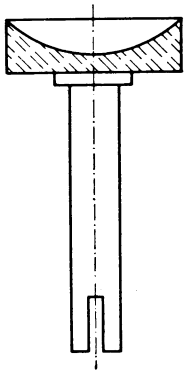


Figure 4.47 First side ground to a sharp edge

The tooling for the next stage must be very carefully prepared. The tool holding the components is cut to a very precise surface curvature and semi-polished, so that it may be checked for radius with a test plate by interference. Its diameter should not be more than 110 mm to avoid thickness variations due to surface curvature radius error on the polished surface of the lens components, and flexure in the holder. Only in this way can the final component thickness be guaranteed.

The block holder can hold approximately 120 components, and they must be cemented in position very carefully, to ensure that the sharp edge of the first side makes a clean and sound contact with the carefully prepared surface of the holder.

The smooth grinding stage that now follows is best done by hand, because in this way the uniformity and symmetry of wear on the block may be controlled to the necessary precision. The minimum thickness removed by polishing will be approximately 0.03 mm, so the centre of the block should show this allowance when measured in the fashion shown in figure 4.48. The edge of the block will normally have a slightly greater (0.05 mm) allowance than this to achieve the

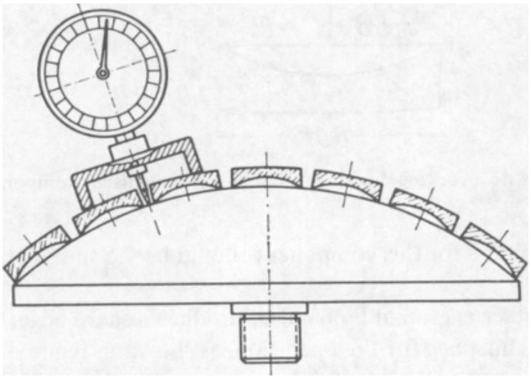


Figure 4.48 Second side of the lenses being ground and polished on a hand block holder

usual edge contact when the polishing is started. For absolute certainty at this stage it is advisable to remove a component from both the centre and the edge of the block to check the centre thicknesses that have to be achieved.

The block of lenses is next polished on a lever-arm machine, great care being taken to avoid dislodging any of the components; this requires that the machine is adjusted to minimum pressure, because the components are only held by their edges with a very delicate bead of cement.

If the required thickness tolerance is to be achieved the polishing craftsman should also do the fine grinding, so that he knows the characteristics of the interaction between the smooth grinding and the polishing and he can adjust the allowances of thickness to match the preferred stroke of the polishing machine, the temperature of the polishing slurry and the polishing medium used.

When the components are finish polished they are removed from the block, cleaned, edged and inspected in the normal way.

(6) Objective front lenses that are made from glass spheres

The glass component closest to the object in high power microscope objectives is often hyper-hemispherical in form (see figure 4.49), which is obviously difficult to manufacture. While it is possible to work such components using conventional techniques, it is more economic to manufacture complete spheres of glass and then

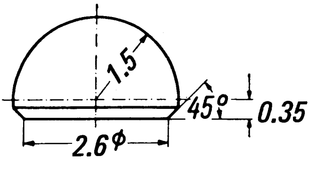


Figure 4.49 Working drawing of a typical front lens for a high power microscope objective

grind and polish the second side as a flat on the sphere. The techniques used to grind and polish the spheres are borrowed from the ball bearing manufacturing processes.

To emphasise the difficulty of working hyper-hemispheres using conventional methods one can see that to achieve the necessary edge contact condition at each stage of smooth grinding and polishing the surface radius, which normally has to be longer for convex surfaces, would in this case have to be shorter. However, achieving such an arrangement would no longer provide the stability of contact and inward progress of wear that is the whole reason for the edge contact, even if it were physically possible to achieve.

The raw material for the component is cut into plates of thickness 1 mm greater than the diameter of the finished spheres. These plates are then cut into cubes and tumbled in a rotating drum with an abrasive lining of silicon carbide to break off the corners.

Figure 4.50 shows the special grinding machine that is employed for the rough grinding. This machine cycles the workpieces automatically through a grinding process that consists of working the glass balls between diamond impregnated or silicon carbide discs, with the balls held in a slowly rotating cage (as shown at *a* in figure 4.50). After passing through the grinding stage, each ball is made to roll along a grading slot of a calibrated varying width, such that it falls into a row of containers underneath if it has reached the required diameter within the specified tolerances. The progress of the diameter of the balls is controlled by a micrometric setting (as shown at *c* in figure 4.50).

The fine grinding process illustrated in figures 4.51–4.53 consists of rotating the balls in 60° conical depressions with an abrasive slurry fed through the back of the grinding tool. The balls are rotated by a rubber-faced driving plate (shown

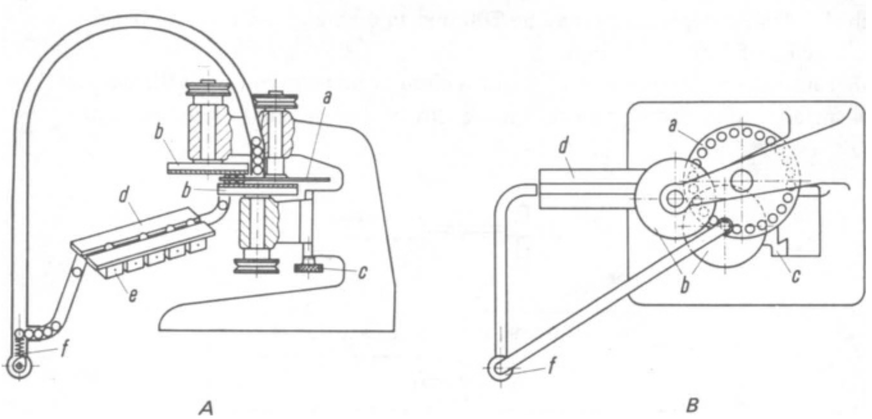


Figure 4.50 Automatic machine for the rough grinding of glass spheres: (A) side view, (B) plan view. *a* Cage for balls during working, *b* silicon carbide or diamond impregnated discs, *c* micrometric adjustment of disc separation, *d* sorting slot guage, *e* collecting baskets, *f* spring arrangement for transporting spheres

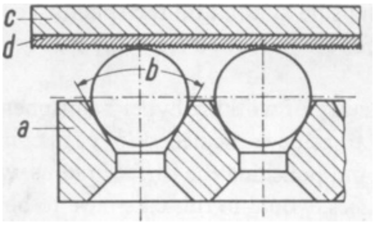


Figure 4.51 Conical depressions in the grinding tool. *a* Grinding tool plate, *b* 60° depression, *c* flat plate to rotate the spheres, *d* rubber facing to grip the spheres

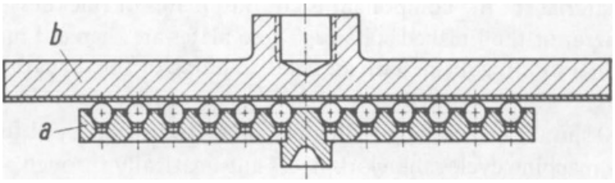


Figure 4.52 Grinding tool plate filled with spheres and placed in contact with the driving plate. *a* Grinding tool plate, *b* driving tool

at *b* in figures 4.52 and 4.53) and the grinding tool and this plate may be worked on the conventional lever-arm optical glassworking machine as shown in figure 4.53.

The rough-ground balls are first loaded into the special grinding tool and the rubber-faced driving disc is placed on top before they are both inverted for working on the lever-arm optical machine. The diameter of the rubber driving disc and the stroke of the machine must obviously be such as to avoid the balls dropping over the edge of the driving disc. For the optical component we are considering the tool with the conical depressions may be 200 mm in diameter, and the rubber driving disc may be 450 mm in diameter.

Because the glass spheres only make a circular line contact with the conical tool surfaces the grinding proceeds more slowly than would be the case with

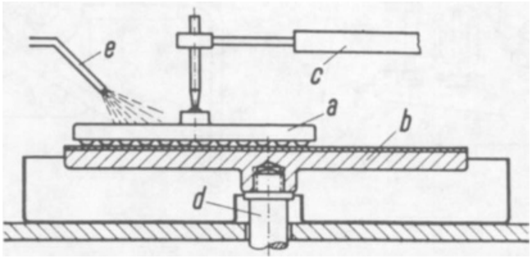


Figure 4.53 Grinding the spheres on a lever-arm optical glassworking machine. *a* Grinding tool plate, *b* flat driving plate, *c* lever of the lever-arm machine, *d* driving spindle, *e* automatic feed of abrasive slurry

conventional fine grinding, but this provides the opportunity for delicate control of diameter and it also reduces the resistance of the balls to rolling. As the work proceeds, however, the conical tool surfaces become worn to a spherical form, the speed of cutting increases and eventually the rolling resistance becomes intolerable, so that the tool has to be recut. With careful mechanical design and tool room metal machining, it is possible to cut the same conical surfaces on both faces of the tool plate, so allowing the plate to be turned over and the lever-arm adaptor threaded into the opposite side. This procedure may or may not be of benefit in any particular workshop.

The polishing process requires batches of fine-ground spheres whose diameters do not vary by more than 0.003 mm, and to achieve this tolerance the fine grinding process must be monitored very carefully. In particular, due regard must be given to any radial variation of cutting speed on the 'block' of balls, so that the machine stroke and selective loading of larger or smaller balls at the edge or the centre may be controlled in a rational manner.

After smooth grinding in this fashion the balls must still be graded for diameter using a slot gauge and collecting buckets so that each batch of balls for polishing is uniform in diameter within the necessary limits.

The material removed by the polishing process corresponds to between 0.01 and 0.02 mm change in diameter of the balls, and although a shorter or longer polishing cycle will remove correspondingly less or more material, it is advisable to prepare the smooth ground balls to within a very tight diameter tolerance for convenience in both batch marshalling and uniformity in polishing cycle time.

The polishing process (illustrated in figure 4.54) consists of placing the smooth ground spheres between two contra-rotating polishers which each has an annular groove of the same cross-sectional radius as the balls. The two polishers are driven at 120 rev./min and the tangential rolling and radial differential frictional forces rotate the balls to achieve an overall polish with the help of a polishing slurry of rouge and water.

It is important that the shape of the polishing grooves should remain constant and for this purpose the pitch used must be harder than is used in conventional polishing. A suitable mixture will consist of coal tar or wood pitch mixed with beech or walnut wood powder. The polishing ring will normally be formed by a heated die, but it may also be formed by turning on a lathe.

The polishing action is only really effective at the top and bottom of the balls, where they are pressed in contact with the polisher, and for this reason the process time is relatively long, leaving the operator free to proceed with other work such as smooth grinding or monitoring other polishers.

The balls in the polisher track must be kept separated, and this is achieved by placing a cellulose ball between each pair of glass spheres, these balls being slightly smaller in diameter than the glass spheres.

The progress of the polishing may be usefully checked with a precision diameter measurement made with a comparator that has been calibrated with a glass sphere whose diameter is correct according to the proof sphere (as verified by the usual

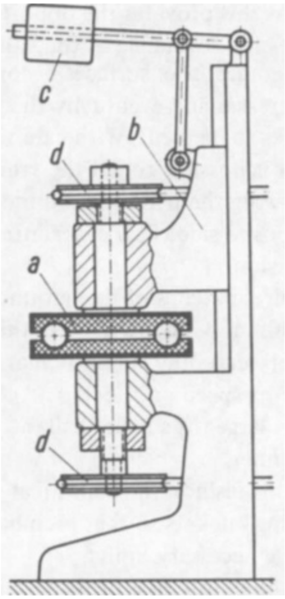


Figure 4.54 Polishing glass spheres. *a* Annular polisher, *b* slide for pressing together the polishers, *c* loading weight for the polishing force, *d* drive wheels

interference method). As the spheres approach their final diameter they must also be checked for uniformity of shape, and where a sphere is irregular it should be put on one side so that it may be corrected in a slow-speed polishing cycle, along with other defective spheres.

The final process in the manufacture of these microscope objective front components is the grinding and polishing of the flat surface, as shown in figure 4.55.

The processes involved in the grinding and polishing of the flat surface are those described elsewhere in this book and are perfectly conventional, although care must be taken to achieve uniformity of thickness at the smooth grinding stage.

Testing and inspection of microscope objectives

Aberrations and dimensional tolerances are usually a direct fraction of the focal length of a lens, thus if we scale a lens system down, we also scale down its

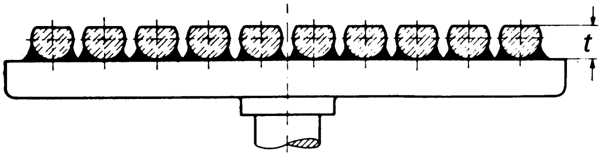


Figure 4.55 Grinding and polishing the flat side of the microscope front lenses: *t* finished thickness. Note that the thickness at the smooth-ground stage will be more than this by 0.005 mm, and this condition must be met at all points in the block

aberrations and tolerances, the former being advantageous, and the latter being an embarrassment. High power microscope objectives may have a focal length as short as 2 mm, and tolerances of, say, ±0.05 mm found in an objective designed for a focal length of 50 mm, when scaled down to a focal length of 2 mm, become 0.002 mm. Fortunately the field angles over which microscope objectives work are much smaller than those encountered in the relatively more sensitive photographic objectives found at longer focal lengths, and this reduces the sensitivity of the performance to manufacturing errors.

Another factor that enters into the tolerancing of microscope objectives is that, loosely speaking, below a certain level, aberrations need not be improved upon: this level is around one-quarter of a wavelength of light (1 wavelength = 0.00055 mm for green light), and thus, if our 50 mm photographic objective has 5 wavelengths of some aberration, it will only have 0.2 wavelengths if the optical system is scaled down to a focal length of 2 mm. The quarter wavelength rule says that at that level of aberration the theoretical performance of the optical system may be regarded as perfect, so allowing a margin for manufacturing errors.

Against this advantage that comes from the scale of the optical system there also emerges the disadvantage of the requirement to resolve much finer image structures, and for any particular microscope objective specification one factor or another takes predominance but one is invariably left with unusually tight tolerances when manufacturing high power microscope objectives.

There are three basic categories of manufacturing error to be found in any optical system:

(1) Surface shape, particularly symmetry.
(2) Separations and thicknesses.
(3) Decentrations and surface tilts.

All three categories play their part in degrading high power microscope objectives in full measure. The first category of error results in axial astigmatism, that is, a difference in focal length between different sections through the complete lens, corresponding to an elliptical interference figure at the surface-testing stage.

The second category results in an error of optical correction, particularly spherical aberration, which may usually be adjusted by changing one of the more sensitive separations.

The third category depends on the mechanical design and the assembly procedures that have been adopted in the specification of the system and any error of this type results in comatic aberration appearing in the centre of the field of view of the microscope. This last category of manufacturing defect is responsible for much of the cost of manufacturing microscope objectives, because its prevention involves the use of special high-precision lathes, hand-controlled mounting of glass components in their cells using ‘burnishing’ (or ‘bezelling’) techniques, and also the use of a special technique of mounting each component in a separate plain cell prior to loading all the cells into a single sleeve.

The inspection and adjustment of the finished microscope objectives must be performed by carefully trained technician inspectors who view the image of a pin hole (made as a defect in an aluminium film) formed by the objective under test. A well-corrected and well-manufactured objective should show a white, sharply defined, circular 'star' image with a very faint ring around it. As the microscope is focused either side of the best image the intensity of the ring should increase equally in either direction, and in the case of an achromatic objective (as opposed to the fluorite and apochromatic types) the central spot should be apple-green inside focus and magenta outside focus ('inside' meaning with the objective too close to the slide). These two conditions correspond to the proper state of adjustment of spherical and chromatic aberration.

If there is any comatic aberration present, this will show itself as a break in the faint ring around the central star image, or in more extreme cases a fully developed comet shape. If this error appears in the centre of the field of view it indicates a badly centred objective, but if it appears symmetrically around the edge of the field of view it may be possible to adjust separations to remove it.

With the exception of modern flat field microscope objectives the image will have field curvature and perhaps astigmatism, which will show themselves at the edge of the field of view. These are inherent defects in conventional microscope objectives and the only possible adjustment usually consists in reducing the astigmatism and tolerating the remaining field curvature.

5

Manufacture of Objectives for Astronomical Instruments

For smaller sizes, up to say 100 mm diameter, the manufacture of achromatic objective lenses and mirrors falls within the normal line of work for the manufacturing optician, although the tolerances on surface quality and glass homogeneity are tighter than normally encountered.

Astronomical instruments are usually used to observe stellar and planetary objects with detail close to the limit of resolution of the instrument. The limit of resolution is set by the wavelength of light, and when expressed in angular terms for an astronomical instrument it is given by the famous equation due to Lord Rayleigh:

$$\text{angular resolution limit} = \frac{1.22\lambda}{D} \text{ radians}$$

where λ is the wavelength of the light and D is the diameter of the aperture of the instrument. So, for example, if we have a telescope with a diameter of 150 mm, and we assume the wavelength of the light is 0.00055 mm, then we will be able to resolve two stars of angular separation 0.00000447 radians, and as each second of arc is 0.00000485 radians, this resolution corresponds to approximately 1 second of arc, that is one 3600th part of a degree.

To observe successfully objects with structural detail close to the limit of resolution, the image-forming wavefronts should, as a general rule, be spherical to within 0.25 wavelength of light, that is 0.00014 mm if the colour of the light is green. Such a wavefront defect may be introduced by an error of 0.5 wavelength on a refracting surface of refractive index 1.5, or 0.125 wavelength on a reflecting surface, so we can see that mirror surfaces are roughly four times more sensitive to surface form errors than are lens surfaces.

The concept of spherical wavefronts perhaps needs some brief explanation. We may consider each point in the field of view of an optical system as the source of diverging rays, or alternatively the source of diverging concentric ripples or wavefronts. These wavefronts leaving each object point are perfectly spherical, and for the corresponding image points we require perfectly concentric converging spherical wavefronts which will generate each image point, all parts of the wavefront arriving simultaneously if the wave is truly spherical. It is the job of the optical system to transform the incident spherical wavefronts into the convergent spherical image-forming wavefronts, and there are always small residual design and manufacturing errors which distort the spherical shape of these image-forming wavefronts. Just as in the case of microscope objectives the residual errors of design are scaled down, in the case of astronomical instruments these residual errors are scaled up, and special corrective polishing called 'figuring' should be applied to the surfaces of the lenses and mirrors to compensate for the inevitable design residuals that have been scaled up with the focal length.

It is the difficulty of figuring and the tendency to elastic distortion of large precision optical components that make their grinding and polishing a specialist branch of optical manufacturing. The manufacture of some of the larger astronomical mirrors has taken many years and the accounts of the work make most exciting reading.

The control of the polishing and figuring process for astronomical surfaces may be monitored in a number of different ways, but there are three tests that are in regular use and which should be mentioned.

(i) The Foucoult knife edge test. In this test the image of a star (artificial or real) is formed by the surface under test close to the pupil of the observer's eye. This image is cut with a knife edge and, if the illuminated view of the surface is darkened simultaneously for all points, the knife edge is at the image point, and any small irregularities in the wavefront show up as bright patches on a dark background. This test is extremely simple, and in the hands of a skilled operator is capable of all the testing that is necessary for even quite large astronomical surfaces.

(ii) The Hartmann test. This test involves placing a perforated mask over the surface to be tested. Each hole isolates a 'ray', and if photographic plates are placed close to the image in more than one plane then a series of spots may be recorded and their positional errors measured and interpreted in terms of surface slope errors or wavefront distortions.

(iii) Interferometric tests. There are many different types of these, but they are all based on comparing the shape of the image-forming wavefronts with some reference wavefront. One of the most successful forms of this test involves 'shearing' the wavefront under test sideways and comparing it with itself; if the wavefront is perfectly spherical the fringes produced will be straight or non-existent, depending on the adjustment of the instrument, and departures of straightness may be interpreted in terms of optical surface errors. This particular form of interferometric test is probably so successful because it involves only small shears of the wavefront, whereas other interferometric tests often pass the reference wavefront through some completely different path and so sensitise the instrument to differential disturbances and vibrations, and in that way destroy the information required.

The information gained by these tests is used to modify the polishing strokes and the polisher shape. In general a ring-shaped polisher will polish a ring on to an optical surface, so if one has detected a ring-shaped hill on the optical surface, it may be worked on by a ring polisher of the same diameter. The total errors on an optical surface can usually be analysed as a series of concentric hills and valleys, and if the polisher is made with equal and opposite polishing rings it will in principle provide the necessary corrective action. Making such rings on a large polisher is not easy and it is usual instead to provide the polisher with a series of radial 'petals' which contain the polisher surface with an angular occupancy representing the degree of wear required at any particular zonal radius in the aperture.

For larger optical surfaces the design of polishers for each stage is usually aided by a computer. Often the information from the test is fed directly to the computer, and petal polisher characteristics are calculated directly.

6

Manufacture of Test Plates

Test plates are of fundamental importance in an optical factory since they act as basic workshop radius and spherometric standards. They are self-checking as far as their sphericity is concerned, because they are made in pairs and may be rotated or sheared with respect to each other and should show the same degree of contact in all relative positions. Their radius calibration is more difficult and this is dealt with separately later.

The grinding and polishing of test plates is similar to that of lens components, except that their centre thickness is not subject to tight tolerances and the quality of the second surface is not usually of any importance.

The material of which test plates are made must be well annealed so that it is stable, and it should be sufficiently hard to resist being scratched.

Suitable glasses are hard crown (including green plate), borosilicate crown, zinc crown or Pyrex, the latter glass being particularly suitable in view of its low coefficient of thermal expansion. Quartz and the special low expansion glasses like Cervit or Zerodur are of course suitable, but they are expensive and their use is only justified where the extra precision they can ensure is absolutely necessary.

The diameter to thickness ratio should be in the region of 5:1 to avoid elastic effects in polishing or during use, and the back surface of the plate should ideally be given a curvature that aids viewing of the fringes when the plates are in use, although frequently the back face is made flat for the convenience of glass procurement and cost of processing.

Both the radius achievement and the correct sphericity are vital if the test plates are to be of use. The initial work is to rough grind a curve close to the required radius and then polish it and check it with existing test plates or a spherometer to reveal whether the radius is correct for the next stage of fine grinding. The whole grinding and polishing process has to be progressed with both halves of the test plate pair and a pair of smooth grinding tools that are progressively corrected as a family while the radius converges on the required value, which usually has a tolerance of ±0.5 per 1000 (0.05 per cent), although some radii will be required to even tighter tolerances than this.

The radius matching between the two halves of the test plate pair should be very close, so that their radii are identical for radius-measurement purposes and also so that the absolute sphericity of the surfaces is fully revealed when they are contacted against each other. The normal standard of radius matching is referred to as 'colour' or 'white band', implying that the interference pattern in white light shows all one colour, and thus in monochromatic light with a slight wedge in the air film the fringes would be straight to within a small fraction of the fringe spacing.

A higher degree of radius matching may be achieved, in which case the reflections from the contacting surfaces disappear, and the contact is referred to as 'black' or 'black band', and under these circumstances the two surfaces may be fused together with the application of heat, owing to the direct molecular attraction across the contact surface.

Flat test plate surfaces are worked in just the same way as spherical surfaces, but they are worked in a group of three. It is then possible to achieve an infinite radius without reference to a spherometer. This technique has the advantage of achieving a perfect plane without any dependence on the calibration of the spherometer, and so for the same reason, the finished plano test plate may be used as an absolute standard of flatness for setting the zero of the spherometer.

In practice a flat test plate will usually be available to start the work, and only when master plates of the highest quality are required will it be necessary to work two others. Clearly, it is possible to work two plates that fit each other perfectly, but that have a long but not infinite radius. Under these circumstances one but not both of the pair may fit a third flat plate, and only when all three fit each other perfectly can they be flat.

Measuring the radii of test plates

The measurement of the radius of test plates may be done with either a conventional spherometer (figure 6.1) which measures the depth of sag of the surfaces in the fashion of a depth micrometer, or with direct radius measurement on an optical bench (figure 6.2).

The specific method of measuring the depth of sag or the radius can be based on any one of a number of techniques, and figures 6.1 and 6.2 are only schematic. The best available method would be based on interferometric length measurement which uses the change in length of the optical path difference in a laser interferometer, combined with automatic photometric fringe counting to give the length directly in wavelengths of monochromatic laser light (usually Helium Neon emission at a wavelength of 0.0006328 mm). Such a system is capable of length resolution to an accuracy of approximately 0.1 or 0.2 wavelength, but the mechanics of the probe contact detection, the elasticity of the spherometer ring and the elasticity of the test plate itself prohibit the possibility of achieving such overall accuracy. The more conventional mechanical length scales with micrometric or glass scale calibration usually provide direct or interpolated readings to an accuracy of 0.001 mm or

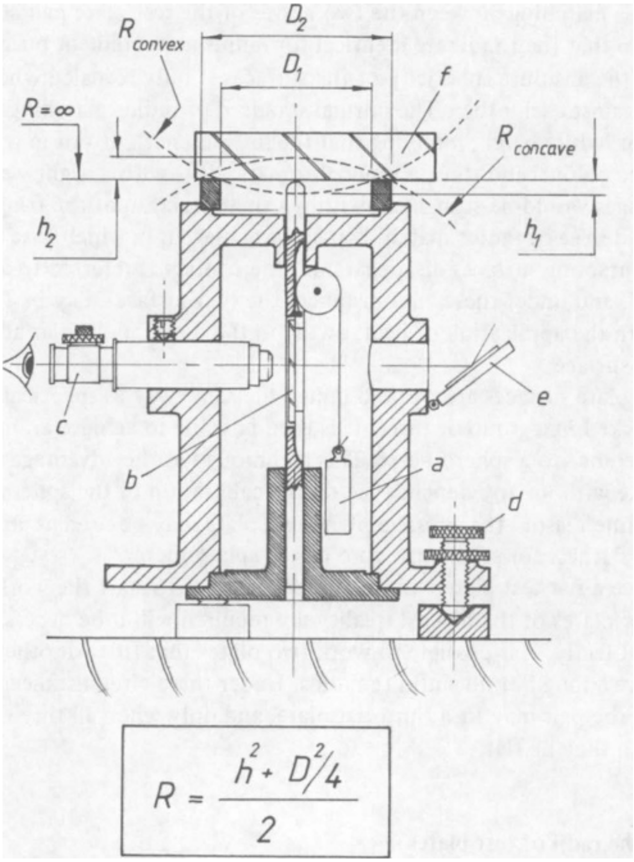


Figure 6.1 Spherometer. h_1 Convex sag, h_2 concave sag, D_1 effective diameter of spherometer ring for convex surfaces, D_2 effective diameter of spherometer ring for concave surfaces, *a* counterweight system, *b* scale, *c* reading microscope, *d* three foot screws, *e* illumination mirror, *f* reference flat

0.0005 mm and this is good enough for all normal optical manufacturing requirements if the precautions mentioned below are taken.

If the radius is to be measured with either of the techniques shown in figures 6.1 and 6.2, the final uncertainty in the radius measurement will be strongly dependent on the diameter of the plate that is measured. In the case of the direct radius-measurement method shown in figure 6.2, the depth of focus at the reflected image will be dependent on the cone angle of the rays forming the image, such that the greater the diameter of the test plate the less will be the uncertainty of the setting. In the case of the technique shown in figure 6.1 it is not quite so easy to see the importance of having a test plate of an adequate diameter, and we have to consider some simple mathematics.

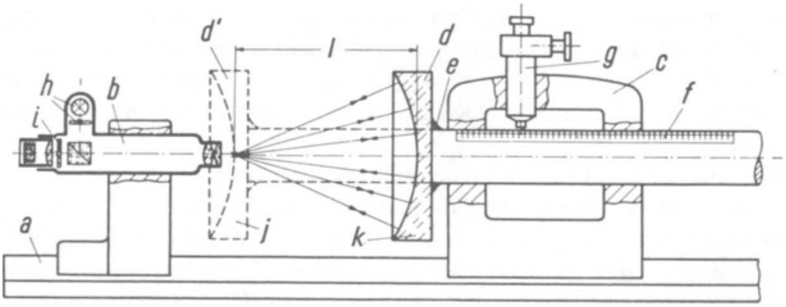


Figure 6.2 Direct radius-measuring instrument. *a* Optical bench, *b* autocollimation microscope, *c* body of length measuring head, *d* test plate, *e* wax, *f* linear scale attaching the test plate to the scale, *g* reading microscope, *h* autocollimation microscope with illuminated graticule, *i* reference graticule, *j* position of test plate to obtain the image reflected from the vertex, *k* position of test plate to obtain the image reflected from the whole surface, *l* surface radius, being the difference between the two settings *j* and *k*

The sag (sagitta) or camber of a surface is given approximately by the following formula

$$\text{sag} = \frac{D^2}{8R}$$

where D is the diameter of the spherometer ring and R is the radius of curvature of the surface.

If we differentiate this expression, using the standard mathematical procedure, we get

$$\frac{\mathrm{d(sag)}}{\mathrm{d}R} = -\frac{D^2}{8R^2}$$

or

$$\mathrm{d}R = -\,\mathrm{d(sag)} \times 8R^2/D^2$$

where $\mathrm{d}R$ is a small change in R and d(sag) is the corresponding small change in the sag. This equation can be interpreted as the error in R resulting from an error in the measurement of the sag, and thus, if we measure a radius of 1000 mm with a spherometer whose linear measurements are uncertain to 0.001 mm (d(sag) = 0.001 mm), and whose ring diameter is 20 mm, then

$$\begin{aligned}\mathrm{d}R &= \text{the error in } R\\ &= 0.001 \times 8 \times 1000^2/20^2\\ &= 20 \text{ mm} = 2 \text{ per cent of } 1000 \text{ mm}\end{aligned}$$

whereas, if the ring diameter is 100 mm, this radius error will be only 0.8 mm = 0.08 per cent.

To avoid marking the surfaces of lenses in production it is necessary to work with a test plate that is just a little larger than the lens surface to be tested and if this is not large enough to achieve the necessary accuracy of radius measurement, then a master test plate pair should be made and smaller production test plates made from them.

It has been stated that radii are required to be known to an accuracy of 0.05 per cent, and yet the example just considered revealed that even with an accuracy of sag measurement of 0.001 mm, an accuracy of only something like 0.08 per cent on radii in the region of 1 m is achieved. There are, however, two precautions that enable better accuracy to be achieved. These are as follows.

(1) Make several measurements of the sags, and take their average. Statistical theory states that whatever uncertainty there is in a measurement will be divided by the square root of the number of readings as long as they are truly independent. Achieving true independence between instrumental readings is not easy but if, for example, we carefully took five separate settings on the spherometer, estimating fractions of a division on the scale of the instrument each time, we should be able to reduce the uncertainty by a factor of

$$\frac{1}{\sqrt{5}} = 0.45$$

that is, roughly one-half.

(2) Measure the radius of both the concave and the convex test plate; any difference in the radius measurements can be attributed to instrumental error, observational error, thermal effects, or the effects of differential elastic deformation in the support ring, the test plates and the reference flat. The average of these two readings will thus have less uncertainty.

The accuracy of long radius measurements is usually limited by the diameter of the test plate or spherometer support ring, while the accuracy of short radius measurements will be limited by the fundamental linear accuracy of the instrument. For example, if we measure a radius of 5 mm using a spherometer with a support ring of diameter 7 mm and a linear uncertainty of 0.001 mm, we expect a basic uncertainty in R of

$$\mathrm{d}R = 0.001 \times 8 \times 5^2/7^2 = 0.004 \text{ mm}$$

which is 0.08 per cent.

Although this proportional error can be improved upon by measuring the concave and convex plates and by taking several readings, there comes a point where the radius is too short to fit on a spherometer of the ring type, and the uncertainty of focal setting for the autocollimating microscope type of spherometer fails in terms of fundamental linear resolution. At this stage, and indeed for all short radii, it is better to manufacture spheres that can be measured directly for diameter, using a linear measuring instrument of appropriate sensitivity.

7

Manufacture of Low-cost Curved Mirrors

There are many applications for mirrors where the surface shape precision need not be of a very high quality. For example, illumination systems in microscopes and projectors, search lights and opthalmoscopes.

Where these mirrors have a spherical surface shape the normal processing methods may be used, except that it is usual to replace pitch as the polishing medium by felt which provides a much faster polishing action.

Where a mirror with an aspheric profile is required it is necessary to introduce special techniques. Such aspheric (non-spherical) shapes may often be conic, that is, elliptic, parabolic, or hyperbolic, but sometimes there will be a requirement for less regular shapes, which will be specified in terms of some set of coordinates or an equation provided by the design department.

The generation of curves using the method of thermal sagging

The simplest method for giving a shape of any specified characteristics to a plate of glass is by allowing the plate to sag on to a cast iron form tool under the influence of heat and vacuum.

Figure 7.1 shows a typical sagging tool arrangement. The form tool (die) is

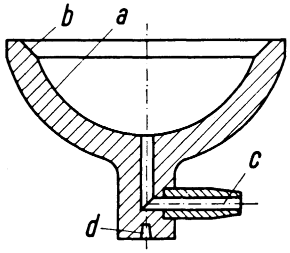


Figure 7.1 Sagging die. *a* Aspheric profile, *b* chamfer, *c* vacuum lead, *d* spigot location for the carrying table

made of cast iron with a fine grain texture which is fine turned to a template or by a numerically controlled lathe. At the vertex of the die, a hole is provided which leads to a vacuum pump.

The die surface is dusted with the absolute minimum of a release agent such as graphite or chalk, and a disc of glass of an appropriate diameter is placed in position before the heat and vacuum are turned on.

The glass is heated to its softening point (see figure 7.2), and then the space beneath the glass is evacuated to draw it into the mould.

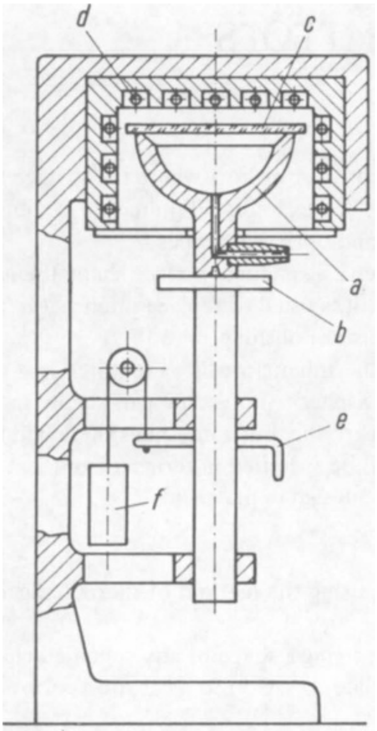


Figure 7.2 Softening oven. *a* Die, *b* carrying table, *c* glass disc, *d* electric heating coil, *e* handle for raising and lowering die, *f* counterweight

The softening temperature for hard crown glass is usually in the region of 710°C but the glass manufacturer will provide a specific value for any particular glass that is to be used.

After the mirror has been formed the die is removed from the carrying table and allowed to cool to a temperature where the mirror can be removed from the die using the sucker shown in figure 7.3.

We shall take as an example a mirror that requires a hole in the centre, such as a mirror for a cinema projector that has the stem of the lamp passing through it. The

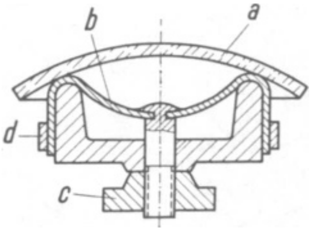


Figure 7.3 Rubber sucking device. *a* Mirror, *b* stretched rubber, *c* handle for stretching rubber, *d* holding ring for the stretched rubber

hole is made with a diamond trepanning tool as shown in figure 7.4, and the edges of the curved mirrors are milled in the fashion of figure 7.5.

If the mirrors are aspheric in profile (paraboloidal, ellipsoidal) it is not possible to work them with a spherical tool of a fixed radius, and it is necessary to process them with a flexible tool as shown in figures 7.6 and 7.7.

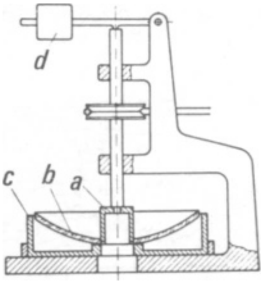


Figure 7.4 Mirror trepanning machine. *a* Trepanning tool, *b* parabolic mirror, *c* holding jig, *d* weight for loading the trepanning tool

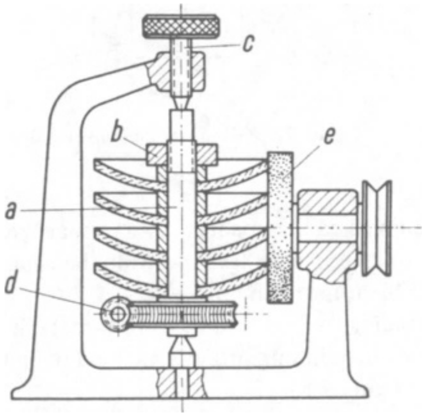


Figure 7.5 Edge milling of mirrors. *a* Mandrel on which the mirrors are mounted, *b* ring, *c* pin for tightening the mandrel, *d* worm drive for rotating the mirrors, *e* diamond tool

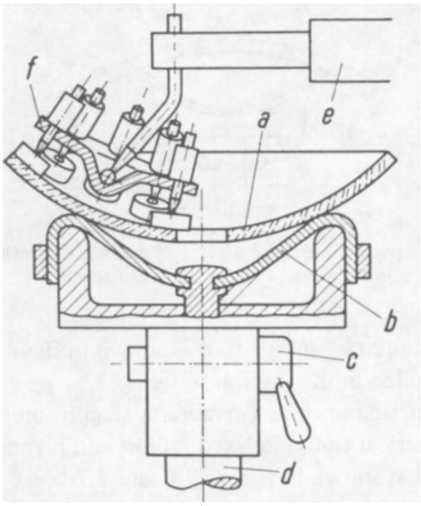


Figure 7.6 Concave grinding machine. *a* Mirror, *b* sucking rubber, *c* eccentric knob for stretching the sucking rubber, *d* spindle of the lever-arm machine, *e* lever arm, *f* dish with spring-loaded grinding heads

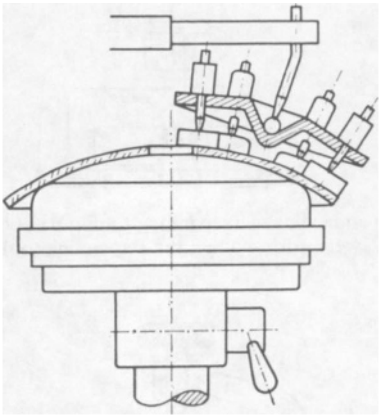


Figure 7.7 Grinding the convex surface

The mirror to be polished may be held by a rubber 'sucker' which is made to work by the action of an eccentric lever drawing the rubber sheet away from the mirror, so holding it by atmospheric pressure.

The cluster of grinding tools is held by a sheet metal hand, and each tool is spring loaded, so that the grinding surfaces are held in contact with the surface that is being worked (see figure 7.8).

For economy in replacement, each grinding tool can be fitted with a working face of lead, so that the main grinding tool is not worn away.

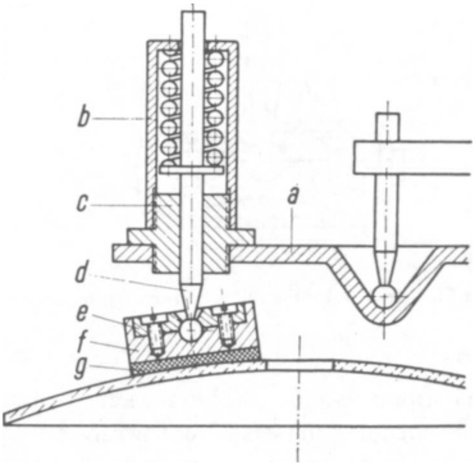


Figure 7.8 Spring-loaded grinding tool. *a* Sheet metal hand, *b* spring loading, *c* bearing for the pressure pin, *d* pressure pin, *e* attachment plate, *f* grinding tool, *g* lead facing for grinding tool

The polishing stage may be completed using the same technique, but with the lead tool facing being replaced by felt, which is fed with polishing rouge rather than the abrasive grit used for grinding (see figure 7.9). The normal procedure will be to polish the concave surface first, because it is the convex surface that is to be made reflective, and if it is done after the concave surface it has less chance of being marked.

The surfaces of the polishers have to be more flexible than the grinding surfaces, and the arrangement shown in figure 7.10 is adopted, which shows the felt polishing material stretched over a former, so that the polisher makes a ring contact with the surface being worked.

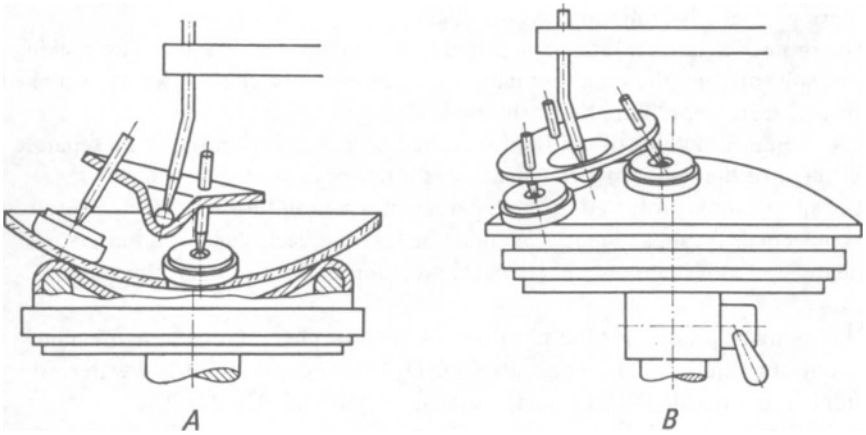


Figure 7.9 Triple polishing head: (A) concave surfaces, (B) convex surfaces

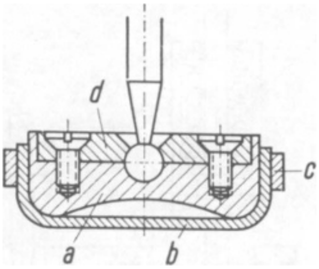


Figure 7.10 Polisher. *a* Former, *b* polishing felt, *c* felt-tightening ring, *d* attachment plate

Both sides of the mirror may be polished in the same fashion, so reducing the quantity of tooling required, but the sets of tooling can usefully be multiplied to the point where each craftsman is operating an economic number of spindles. For mirrors up to 250 mm diameter it is possible with the techniques described here for one craftsman to operate 20 spindles. For mirrors up to 600 mm in diameter one craftsman can operate up to six spindles, and for work up to 1500 mm in diameter three spindles will be as many as one craftsman can handle.

Rubber suction adaptors are not suitable for components larger than 250 mm in diameter because of the higher polishing loads, and these must be cemented to a backing shell.

The quality of the polishing may be observed with a 60 watt lamp and a X6 magnifier, and when a suitable finish has been achieved the surface is lacquered for protection while the second side is completed.

The reflective surface for these mirrors can be most economically applied by chemical silvering, although if large-scale vacuum equipment is available it may be possible to reduce cost by applying silver or aluminium using vacuum deposition. In either case, the mirrors have to be thoroughly cleaned of all traces of rouge, which will have particularly contaminated the edges.

The protective lacquer may be removed by boiling in caustic soda or by soaking in organic solvents, and the rouge-contaminated edges may be cleaned with felt soaked in vinegar, acetone or dilute hydrochloric acid.

The chemical silvering of the finish-polished mirrors is undertaken by a separate department of the factory where chemical laboratory facilities are available.

The silver film is protected by a copper layer, which in turn is protected by a suitable lacquer finish, and great care must be taken at each stage to achieve an adequate level of cleanliness and chemical precision in the mixing of the various solutions.

The chemical process for the silver film consists of precipitating pure metallic silver out of a solution of silver nitrate ($AgNO_3$) made up with distilled water, ammonium hydroxide (NH_4OH) and potassium hydroxide (KOH). The precipitation is achieved by the use of a reducing solution made with cane sugar, nitric acid, alcohol and distilled water. The detailed process, first developed by

Brashear, involves careful chemical laboratory control and clean and precise work by the craftsmen.

Where a large number of optical surfaces are to be chemically silvered the following procedure may be followed.

First the surfaces are cleaned with stannous oxalate and distilled water, using a stiff hair brush, care being taken to clean every part of the surface and finally to remove all traces of the stannous oxalate.

The mirrors are then placed in transparent rotating or rocking trays, provided with a lamp underneath to monitor the thickness of the film, and jars of silvering and reducing solutions are mounted above so that each new mirror may be treated with a fresh supply of chemicals. If the silvering and reducing solutions are mixed as they are poured on to the mirrors, the process is speeded up, and a convenient arrangement is shown in figures 7.11 and 7.12.

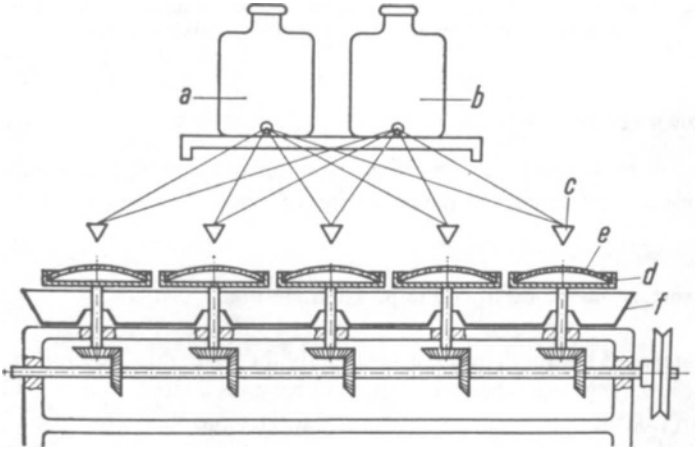


Figure 7.11 Silvering bench. *a* Container for silver solution, *b* container for sugar-reducing solution, *c* mixing chamber, *d* rotating or rocking dishes, *e* mirror, *f* collecting bowl for waste solutions

The correct thickness of silver film is judged by the brightness of the lamp filament seen through the film, but this requires the cleaning of a patch on the transparent tray before each mirror is started; experienced silvering workmen will know from the subtleties of the appearance of the film whether it is thick enough or not. In particular the film will assume a milky appearance when it is of an appropriate thickness, and this test, combined with a confidence in the temperature and concentration of the solutions being used, will enable the work to proceed rapidly and reliably.

The coppering process is not so sensitive and it may be achieved by electrodeposition, or by chemical precipitation, depending on the facilities available and the number of mirrors involved.

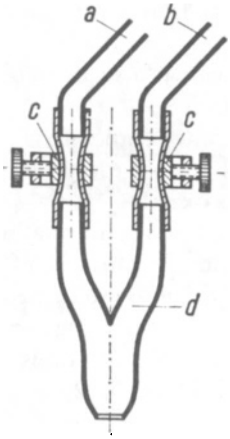


Figure 7.12 Mixing nozzle. *a* Lead for silver solution, *b* lead for sugar-reducing solution, *c* clamps on rubber tubing to control flow, *d* mixing chamber

Testing low-precision mirrors

The testing of these low-precision optical components may be best achieved by setting up some test based on the application for which the component is intended.

Aspheric surfaces made by the oil impression method

Surfaces prepared by the thermal sagging method are suitable only for surfaces of the lowest accuracy, and when an instrument requires a more precise shape of optical surface it is necessary to monitor the surface profile during manufacture. A suitable technique for monitoring surface shape in this situation involves the use of a precision glass template smeared with oil, which shows its contact points on the optical surface as dark patches. As the work proceeds the dark contact patches spread until they are seen all along the edge of the template.

The types of surface that require this degree of control during manufacture are mirrors intended for precision search lights and navigation lights used on ships.

The glass blank will normally be preformed by the thermal sagging method and then milled on a machine of the type shown in figure 7.13, which copies the shape of a metal template on to the surface as it is rotated. Both the convex and concave surfaces may be ground like this by the substitution of suitable templates. The rotation of the optical surface and the traverse of the diamond milling cutter are coupled, so that the generation of the complete surface can be completed automatically, and in this way the operator may control several machines.

For the fine grinding and surface correction stage, a precision glass gauge template is required and the preparation of this is performed on the special machine shown in figure 7.14.

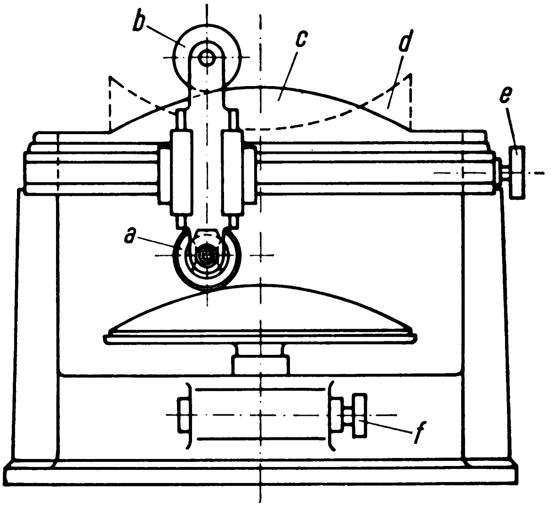


Figure 7.13 Milling machine for profile copying. *a* Diamond milling cutter driven by a motor, *b* template following roller, *c* template for the convex surface, *d* template for the concave surface, *e* mechanism for traversing the diamond cutter, *f* drive for the rotation of the optical component

The diamond milling cutter is guided by the steel strip which is held under tension by the loading weight. The roll-off template that is used to control this process must be prepared very carefully, either by numerically controlled milling or by precise hand work using a file to profile the plate to a scribed line.

The principle on which the roll-off template works is related to the radius of curvature of the glass gauge template at the point that is being milled at any one instant. The radius of curvature generated on the glass workpiece at each point is clearly the length of steel strip that is free of the roll-off template at that point, minus or plus the radius of the milling cutter. Thus in the example shown in figure 7.14 the radius of curvature of the optical profile is short near its centre and longer at the edge, and in general, the more curved the roll-off template, the slower the change in radius of curvature of the optical profile that is generated. Should there be any irregularities in the roll-off template they merely produce a circular arc on the optical profile, while the roll-off point on the steel strip is delayed in its progress along the template. In this way it is easy to see that a sharp discontinuity in the roll-off template does not produce a sharp discontinuity on the optical profile, and it is this tolerance to irregularities on the roll-off template that makes the whole scheme feasible.

The rough milled optical surfaces are next fine ground with spring-loaded cluster tools of the type shown in figures 7.6–7.8. This grinding is continued until the rough grinding tool marks are removed and it is possible to apply the oiled gauge that has been cut on the roll-off template cutting machine.

The next stage is to work on those zones of the aspheric surface that have been

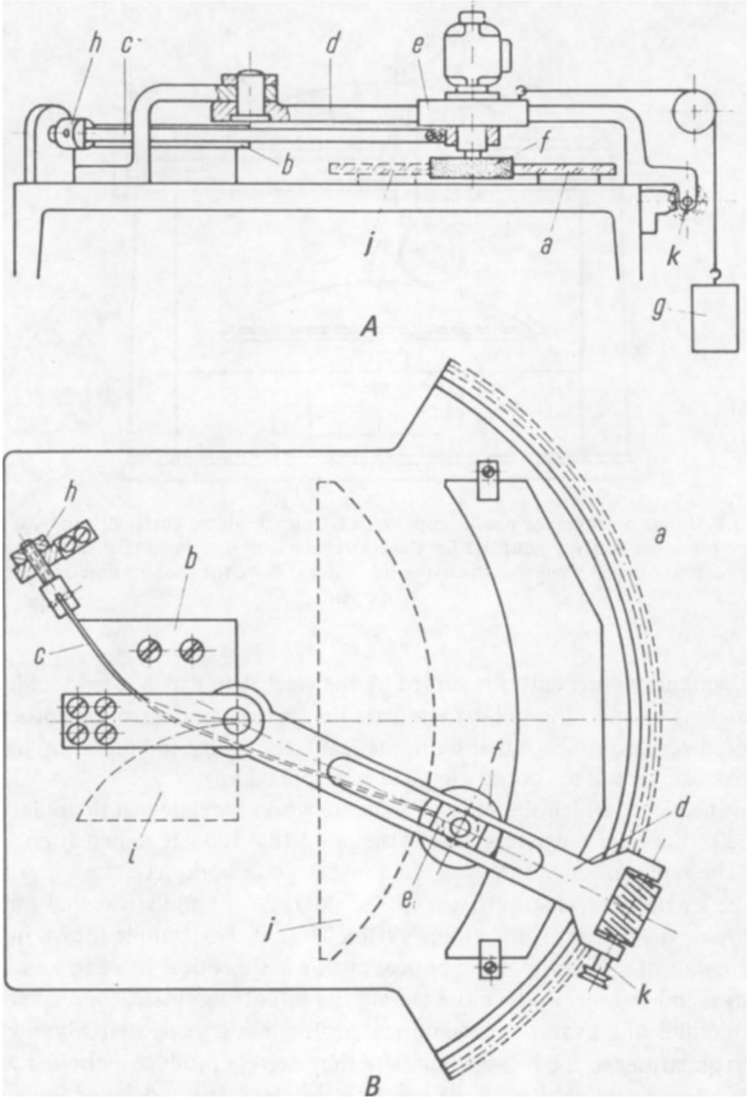


Figure 7.14 Template milling machine: (A) side view, (B) plan view. *a* Glass template (for a convex surface), *b* roll-off template, *c* steel strip, *d* swinging arm, *e* tool guide slot, *f* diamond tool with motor drive, *g* loading weight, *h* clamping of the steel strip, *i* opposite alternative position for the roll-off template, *j* glass template for a concave surface, *k* drive for the swinging arm

shown to be high, using the machine depicted in figure 7.15. This machine is controlled directly by hand, the craftsman choosing how long to dwell on each zone of the surface while the workpiece rotates automatically.

As the smooth grinding proceeds the stiff grinding pad is replaced by a flexible

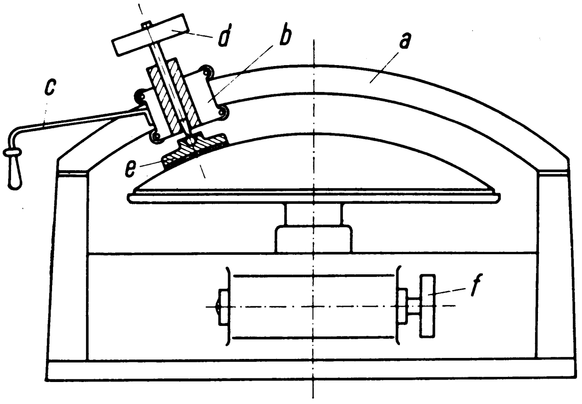


Figure 7.15 Hand-controlled figuring machine. *a* Tool grinding beam, *b* grinding tool carriage, *c* handle for moving the carriage, *d* loading weight for the grinding pressure, *e* lead-faced grinding tool, *f* drive for rotating the mirror

spring-backed tool such as is shown in figure 7.16, to provide better averaging across the irregularities.

At this stage the aspheric surface may be polished with the type of cluster polisher shown in figures 7.9 and 7.10.

An alternative method of grinding which avoids the use of highly skilled hand correction for the profile, represents the most refined of these methods of low-cost aspheric manufacture, and this is now described.

Aspheric form correction using an adjustable grinding strip

The machine used for this method is shown in figure 7.17. The arrangement consists of a flexible strip lying across the centre of the surface that is to be ground, the strip being loaded by a series of rollers which may be adjusted independently to achieve the required profile.

As the machine rotates the optical surface it also oscillates the flexible strip with

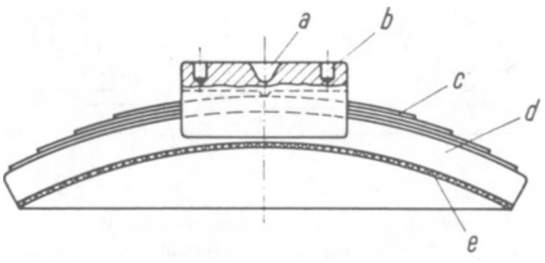


Figure 7.16 Semi-stiff grinding tool. *a* Location point for driving pin, *b* restraining point for driving pin, *c* spring strips, *d* medium hard solid rubber, *e* lead facing attached to the rubber

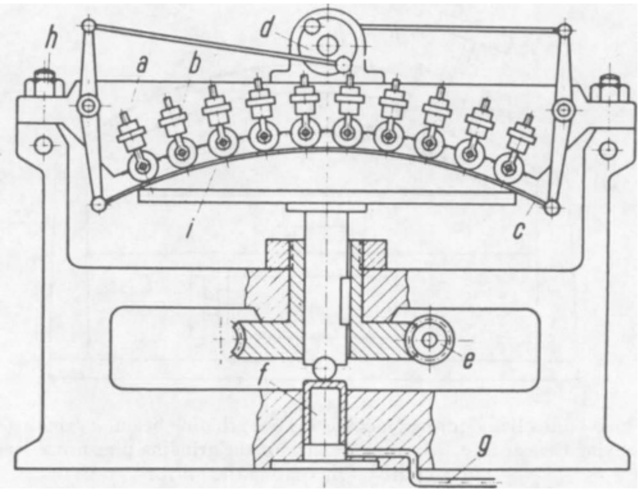


Figure 7.17 Adjustable grinding strip machine. *a* Bridge carrying adjustable rollers, *b* adjustable rollers, *c* steel strip with grinding laps, *d* shaft drive for the strip oscillation, *e* drive for the mirror rotation, *f* hydraulic cylinder to load the optical surface against the grinding strip, *g* hydraulic lead, *h* bridge attachment nuts, *i* optical component

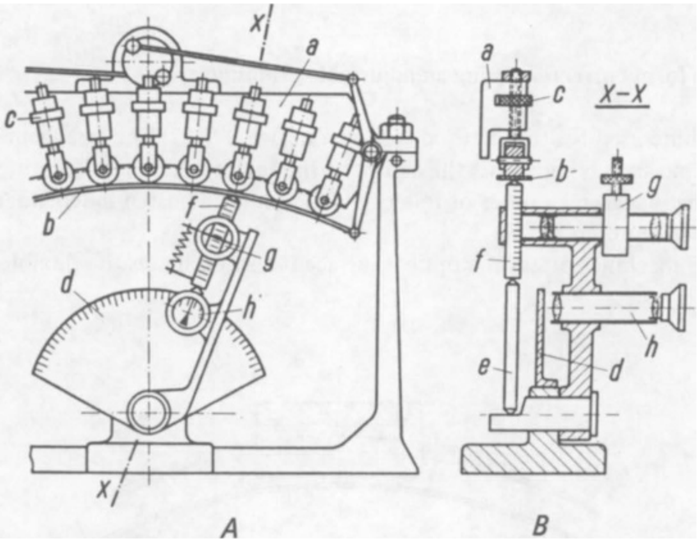


Figure 7.18 Radius pivot microscope: (A) front view, (B) side view on section XX. *a* Bridge carrying rollers, *b* steel strip with grinding facets, *c* adjustment nuts for positioning the rollers, *d* circular scale, *e* length bar, *f* glass linear scale, *g* measuring microscope for linear scale, *h* reading microscope for angular scale

the lever arrangement shown, so averaging the wear applied by any particular point on the strip across a small range of zones.

The adjustment of the template rollers is the most difficult part of the machine adjustment and involves the use of the measuring equipment shown in figures 7.18 and 7.19.

The initial setting of the grinding strip is accomplished using the microscope on a radius pivot as shown in figure 7.18. Having achieved the correct profile, the dial gauge comparator shown in figures 7.19 and 7.20 may be set to it, so that each

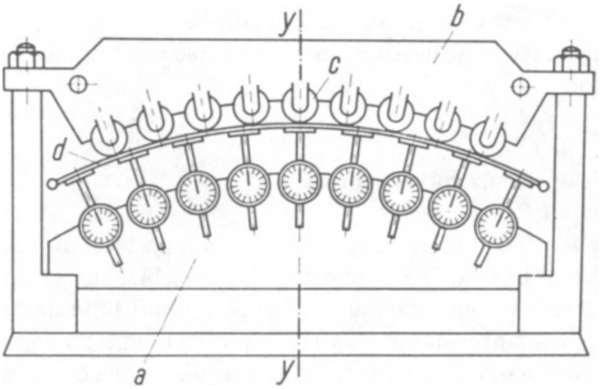


Figure 7.19 Comparator gauge. *a* Arc template beam for holding the dial indicators, *b* bridge with rollers, *c* rollers, *d* grinding strip with facets

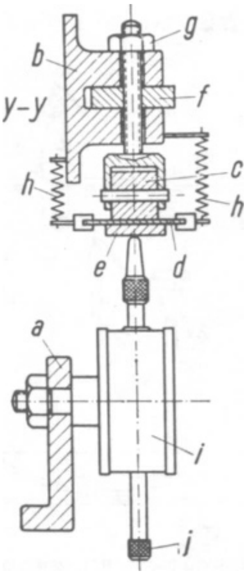


Figure 7.20 Section of the comparator gauge on YY. *a* Arc template beam for holding the dial indicators, *b* bridge with rollers, *c* rollers, *d* grinding strip, *e* grinding facets, *f* adjusting nut, *g* lock nut, *h* springs, *i* dial indicator, *j* fine adjustment control for dial indicator

dial indicator reads zero before any grinding work is started. As the grinding lap faces get worn more at the edge of the surface owing to the peripheral speed of the optical surface, it is necessary to adjust the rollers using the comparator at frequent intervals. This technique, combined with the oil impression gauging method described in the previous section, allows the operator to make localised corrections to the profile based on the comparator dial readings and so arrive at settings that yield well-corrected profiles.

Both the concave and convex surfaces of the mirror blank will normally have to be ground, and the concave side should be processed first to minimise the cosmetic blemishes on the convex surface that is to be silvered.

The polishing may be achieved by using the triple pad technique described in the previous section.

Optical testing of steeply curved mirrors

Depending on the mirror profile and the testing equipment that is available, there are many different techniques of optical testing available, but we shall content ourselves by describing one arrangement that is appropriate to the testing of paraboloids. This arrangement is shown in figure 7.21, where a point source is positioned at the focus of the mirror, and the angular errors of the collimated beam are read by a telescope mounted on a measuring beam.

A refinement of the method shown in figure 7.21, which allows a more systematic correction of the mirror errors, is to replace the telescope with a camera and to draw film through it as it is traversed across the aperture of the mirror, so

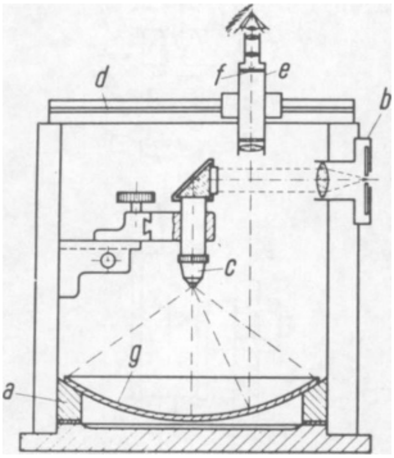


Figure 7.21 Mirror testing apparatus. *a* Base datum, *b* arc lamp, *c* microscope objective forming a reduced image of the arc at the focus of the paraboloid, *d* measuring beam (shown in the plane of the diagram whereas it would normally be perpendicular to it), *e* telescope or camera, *f* graticule of telescope, *g* mirror

recording a track on the film which is directly related to the angular errors of the mirror.

Careful calibration and application of this measuring apparatus, combined with adjustment of the strip grinding machine, allows the quantity manufacture of surfaces whose profiles are correct to within slope errors of ±0.5 minutes of arc, that is ±1 minutes of arc of ray deviation.

8

Manufacture of Aspheric Surfaces on Lenses

The method described in the previous chapter is, of course, not only applicable to the surfaces of mirrors, but may also be used for any long radius surface that does not depart much from a spherical form.

For short radius surfaces with large departures from the spherical form, such as are found on condenser lenses, the field lenses of eyepieces and 'bullseye' signal lamp lenses, a different technique is required, which will now be described. This technique is not sufficiently accurate for the surfaces of optical components intended for telescopic or photographic applications, where the whole aspheric surface is involved in forming each point of a high-resolution image.

We shall consider as an example the eyepiece field lens shown in figure 8.1, which has one aspheric surface and one spherical surface. For the purpose of creating datum surfaces the spherical side of the component is ground and polished first, using conventional techniques. Next, the edge and chamfer are ground true to the completed spherical surface and the component is mounted in a precision holder, as shown in figure 8.2. The precision holder shown here is provided with a datum shank which must be true with the lens seating surfaces.

For economic production quantities, several lenses in their precision holders are mounted on the multiple spindles of a special-purpose profile milling machine such

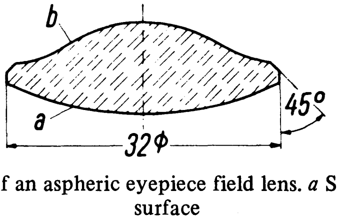


Figure 8.1 Working drawing of an aspheric eyepiece field lens. *a* Spherical surface, *b* aspheric surface

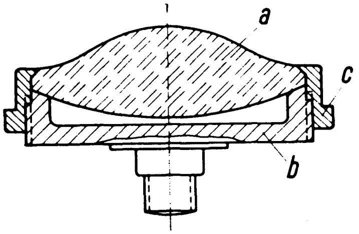


Figure 8.2 Aspheric lens component in precision holder. *a* Lens component, *b* precision holder, *c* clamp ring

as is shown in figure 8.3. The machine layout shown here is only schematic and the machine tool designer can exercise considerable ingenuity in the detailed design of any machine intended for this work. In particular, an adjustment for cutter wear should be included in the design of the machine, but because the cutters retain their circular form this can, in principle, be a simple micrometric feed.

The machine configuration shown in figure 8.3 copies the template profile at the same scale on to the lens blanks, and we should aim for a profile that is accurate to within ±0.05 mm.

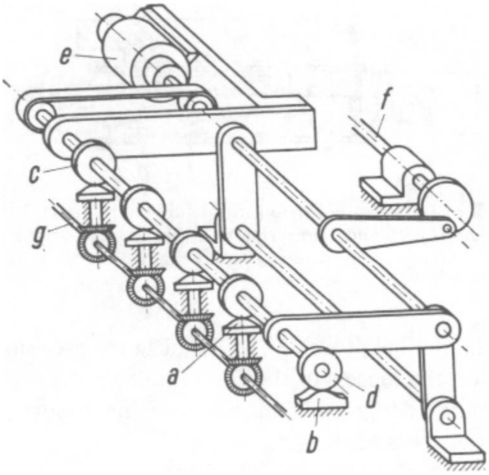


Figure 8.3 Schematic layout for copy milling machine for aspheric lens surfaces. *a* Lenses, *b* template of master curve, *c* diamond milling tools, *d* follower wheel, *e* drive for milling cutters, *f* eccentric drive for traversing the cutters over the lenses, *g* drive for lens spindles

The cutting lubricant used in this process is mineral oil and the cutters are diamond grit embedded in copper.

The next process is to smooth grind the profile that has been generated on the lens blanks, using a machine of the type shown in figures 8.4 and 8.5.

The final polishing process is intended to retain the surface profile generated by

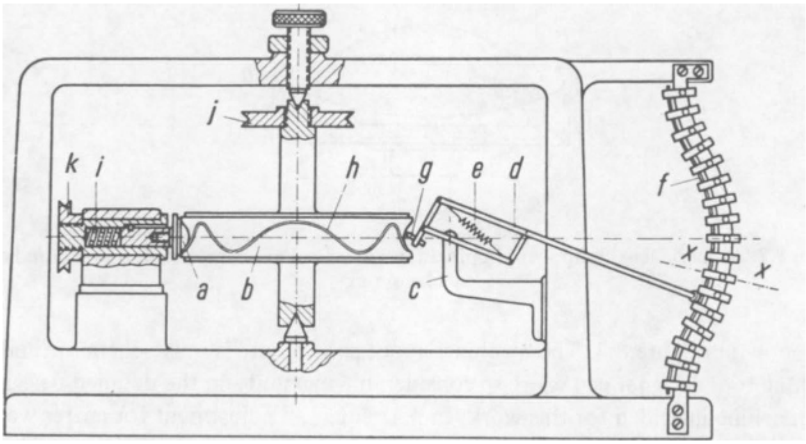


Figure 8.4 Aspheric fine grinding machine. *a* Lens, *b* grinding wheel, *c* wheel dressing mechanism support, *d* pantograph, *e* tension spring, *f* flexible steel strip profile guide, *g* diamond bit for dressing the wheel profile, *h* groove for distributing grinding slurry, *i* spring for loading the lens against grinding wheel, *j* drive for the grinding wheel, *k* drive for rotating the lenses

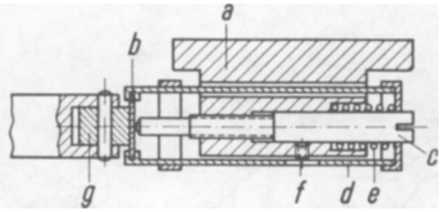


Figure 8.5 Section on XX of flexible steel strip profile guide. *a* Support for the steel strip, *b* steel strip, *c* adjusting screw, *d* jaws and clamp ring to hold the steel strip, *e* spring loading, *f* tightening screw, *g* following roller

the milling and smooth grinding processes, so the ultimate precision of the polished surface depends more on the success of the fine grinding process than on anything else, and for this reason the design and adjustment of the smooth grinding machine must be given the greatest possible attention.

The machine consists of several lens holding work stations arranged radially around the rim of the grinding wheel. The centration and aspheric profile of the finished lenses depend on the adjustment of the centre lines of the work holders being perpendicular to the axis of the grinding wheel, and being set at the same level as the plane of symmetry of the aspheric curve.

The grinding wheel is made of aluminium or brass, and to achieve a uniform distribution of grinding slurry a snake-like groove is milled in the profiled periphery of the wheel. The edge profile of the wheel is almost continuously dressed (and anyway certainly between each grade of abrasive) using a pantograph reduction from the steel strip template, which is adjusted with the aid of equipment of the type shown in figures 7.18 and 7.19 to a profile accuracy of ±0.025 mm. The pantograph reduction brings the dressed wheel profile to an accuracy of ±0.005 mm.

The grinding mechanism does not involve the systematic breakdown of the abrasive powders, so to achieve the very fine surface texture required to proceed successfully to high-speed flexible polishing it is necessary to use several grades of abrasive powder, finishing with special quartz powders for the very finest surface.

The polishing and checking of conventional spherical surfaces depends for its efficiency and success on three important factors:

(i) The sliding fit properties of mating spheres.
(ii) The test plate gauge.
(iii) The stable progression of wear from the edge of the surface or block towards the centre, culminating in a surface that is polished all over, and that simultaneously has the correct radius of curvature.

When an aspheric surface of the type now described is being polished, none of these factors are helpful, and we are dependent on the smooth ground surface retaining its shape by virtue of polishing all points on the surface simultaneously with a high level of uniformity. It is possible to use a test plate with an aspheric profile, but the requirement to centre the test plate and the lens with respect to each other makes it almost impossible to use this technique efficiently.

The polishing is achieved with the machine and polishing tool arrangement shown in figures 8.6 and 8.7. The polishing tool consists of a sponge rubber pad stuck to a metal former of an appropriate profile, and with a facing of felt. The adjustment of the stroke and speed of the polishing machine to achieve a uniform polishing action for all points on the lens surface calls for the traditional skills of the glass worker. It is the achievement of this uniform polishing action, together with the careful adjustment and operation of the smooth grinding machine, that results in the successful flow of production.

The uniformity of polishing is checked at an early stage by examining its progress with the help of a magnifier, particular attention being paid to the zonal regularity of the polish. The final profile may be checked for regularity in the fashion illustrated in figure 8.8, which shows an illuminated pin hole placed at some distance from the lens, such that a large disc of light is formed on a screen. The zonal distribution of light on the screen will depend on the precise aspheric profile under consideration and also on the regularity of that profile, errors of which will show up as dark and bright rings within the more or less uniform patch of light on the screen. This technique is obviously not quantitative, but it does identify which zones of the lens are irregular, and in combination with the examination of the part-polished aspheric surface, it is possible to identify the source of the problem as being associated with either the grinding or polishing stage of the process. Further diagnostic information may be obtained if the spot projection method is used with a reference lens that has been verified as correct, so that a direct comparison may be made between a correct lens and a production sample.

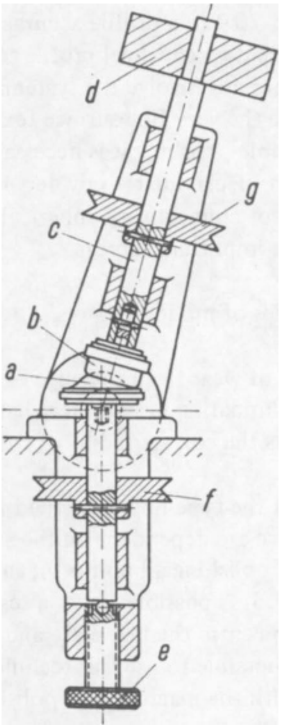


Figure 8.6 Polishing aspheric lenses. *a* Lens, *b* polishing tool, *c* swinging spindle, *d* weight for the application of the polishing force, *e* micrometric adjustment of lens position with respect to the pivot axis of the polishing spindle to achieve uniform polishing, *f* drive for the lower spindle, *g* drive for the swinging spindle

In principle, this sequence of operations and tests will reveal to the craftsman who is controlling the processing just where in the sequence the fault has arisen, and failing all else will allow him to adjust the shape of the template used to generate the profile of the smooth grinding wheel and thus compensate the errors, whether they occur at the grinding stage or the polishing stage.

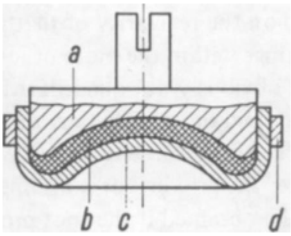


Figure 8.7 Polisher for aspheric lenses. *a* Metal backing former for the polisher, *b* sponge rubber lining, *c* felt facing, *d* circlip clamp

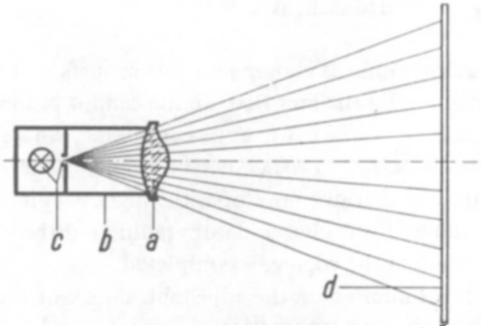


Figure 8.8 Comparator test for aspheric lenses. *a* Aspheric lens, *b* collimator tube, *c* pin hole, *d* screen

Numerically controlled aspheric surface cutting using specialist lathes and milling machines

Modern transducer, metrological and microprocessor technologies have opened the way to a more simplistic approach to the manufacturing of aspheric surfaces, based on the direct machining of the profile with a single point diamond tool or a high-speed diamond grit grinding wheel.

A lathe naturally produces conical surfaces if its tool slideways are straight, and in normal machine shop use these slideways are not only straight but perpendicular or parallel to the centre line of rotation of the workpiece, so that the conical surfaces produced are actually the special cases of the cone that are either cylinders or flat surfaces. A simple addition to the lathe of a pivoting tool post allows the machining of toric surfaces, and these become spheres in the special case where the pivot axis lies on the centre line of the lathe. If the tool is also provided with adjustment along the radial arm of the pivoting tool post it is possible to cut deformed spherical curves and toric surfaces of revolution, that is, rotationally symmetric, aspheric surfaces.

This is the principle of the numerically controlled aspheric lathe. The implementation of this principle is attended by a number of practical difficulties and these are enhanced by the fact that to justify the cost of such a specialist lathe with numerical control and a pivoting tool post, it must be possible to reach precisions that allow the cutting of surfaces destined for high-quality applications. Such applications are where the whole of the aspheric surface is involved in the deformation of a single wavefront – such applications are found in telescopic and photographic optics. It must be admitted that the most successful application of these techniques has been in the cutting of surfaces for infrared optical systems, where the wavelength of the radiation is longer than in the visible spectrum, and so the tolerances on surface texture and shape are slacker.

The procedure for cutting a typical rotationally symmetric aspheric curve on such a numerically controlled lathe is as follows.

(1) A suitable spherical radius is chosen as a datum surface. The choice of spherical datum surface is dictated by the fact that a lathe cannot put material on, and neither is it very good at taking material off near its centre line, where the cutting speed is low. These considerations lead to the choice of a sphere that is tangential to the aspheric at its centre and that just envelopes the highest points of the asphere.
(2) A lens is prepared with the chosen datum radius and the processing of both sides of the lens, including the edging, is completed.
(3) The component is mounted on the adjustable chuck of the lathe and centred and made true so that the common optical and mechanical axes are both coincident with the rotational centre line of the lathe. This adjustment will normally be achieved with the aid of a metrological probe which is provided with a variable sensitivity electronic display so that when the lens component is centred the probe reading will be stationary to within the necessary precision for both the spherical surface and the edge of the lens.
(4) A similar electronic metrological probe is mounted on the pivoting tool post so that its tip is in the same position as the active point of the tool that will subsequently cut the surface. The tool post is rotated about its pivot and the pivot position adjusted until it coincides with the centre of curvature of the datum sphere, that is, until the readout of the probe is stationary when the tool post is rotated.
(5) The metrological probe is replaced by the cutting tool, which must have the same effective length as the probe, and the pivot radius is adjusted so that when the tool is traversed under numerical control it starts to cut at the deepest part of the aspheric profile.
(6) The tool is fed along the radius arm of the pivoting tool post between traverses, by numerical control until the complete asphere is cut.
(7) The metrological probe is substituted for the cutting tool again and the errors of the profile are recorded. The numerical control program is modified and then as many corrective numerically controlled traverses as are required to complete the surface are made.

The last step in this procedure may be applied to the finish polished asphere as well, to compensate for systematic errors in the polishing, but this involves a particularly difficult resetting procedure and would normally only be done on a prototype component to calibrate the numerical program for production quantities.

For the overall success of this procedure particular attention must also be given to the geometry of the tip of the cutting tool whether it be a single point diamond or a grinding wheel rim profile. The particular geometry of the active tip of the tool is, of course, involved in the calculation of the numerical control locus, which is where microprocessor control can be particularly useful, to compensate for changes in tool profile resulting from wear or a change of tool.

A disadvantage of the lathe as a generator of high-quality rotationally symmetric aspheres is that the surface cutting speed varies across the surface, owing to the change in the radius of swing, and this can have a detrimental effect on the surface texture, especially close to the centre of the surface. This may not be so important if a polishing process follows the numerically controlled machining and this polishing is well controlled and capable of smoothing out such irregularities. However, if the surface is cylindrical, toric, spherical or flat, there is in any case an alternative technique that gets over this problem, namely single point fly milling.

Single point fly milling naturally produces cylinders if the traverse is straight, or toric surfaces if the traverse is circular, and in the appropriate special cases these three-dimensional surfaces become spheres and planes. Because the surface cutting speed remains constant it is possible to achieve improved surface textures on these particular classes of surface. This last mentioned advantage is modified in the case of spherical surfaces, where a carefully adjusted fly-milling machine produces a surface traversed by tooling traces which cross each other at every point on the surface, so making it possible to achieve an even higher degree of surface texture quality and, incidentally, machine adjustment, than in most situations where optical surfaces are directly machined. Even in this case the criss-crossed tooling traces are closer together at the centre of the surface than at the edge, and there can sometimes be an advantage in cutting spherical surfaces off-axis to avoid the axial point, where every trace intersects every other trace.

9

Manufacture of Prisms

The manufacturing procedures that are applied to prisms depend on the use to which the final prism will be put. Prisms with superficially similar forms often have very different tolerancing schemes, depending on where they occur in an optical pathway and whether they are used as reflecting elements or refractive deviating elements.

With the exception of prisms for spectroscopic applications most prisms are used as reflecting elements, and it is worth listing the advantages and disadvantages that they offer compared with simple mirrors:

Advantages

(i) Angular stability where more than one mirror is replaced by a prism.
(ii) Natural provision of optical and mechanical datum surfaces which are parallel to and/or perpendicular to the optical axis.
(iii) Easy to clean.
(iv) High, achromatic reflectivity when total internal reflection is utilised.
(v) Lower total optical pathway cross-section, because the thickness of a mirror has to be outside the optical pathway.
(vi) High stability support for the reflecting faces.

Disadvantages

(i) Weight.
(ii) High material cost.
(iii) Optical path has to be transmitted through the glass material of the prism.
(iv) Additional air–glass surfaces.
(v) Increased total optical pathway, owing to the extension effect of the equivalent glass blocks.
(vi) More optical and mechanical surfaces to be worked.

With modern high-vacuum thin-film coating technology, mirrors with high achromatic reflectivity can be manufactured and may be provided with a mechanical overcoat that protects them during cleaning, so in this sense mirrors are more competitive than they were when many of the reflecting prism systems were first designed. Another technical development in favour of mirrors is the availability of special low-expansion glass–ceramic materials which are thermally stable. On the other hand, the transmitting faces of prisms may now be coated with highly efficient antireflection coatings which improve their overall transmission, so when there is a choice between specifying prisms and mirrors it may be a relatively complicated decision, depending more than anything else on the manufacturing facilities that are available for both optical and mechanical components.

Compared with lenses there are three notable areas of high cost involved in the manufacture of prisms:

(1) Any face that is used as a reflector has to be worked absolutely flat, otherwise it is a source of astigmatism.
(2) Roof edge reflecting surfaces that split the aperture have to be worked to 90° ± a few seconds of arc.
(3) The material from which prisms are made has to be particularly homogeneous and free from stress, owing to the long and often tortuous path that the optical axis follows through the prism.

As a result of these influences there are usually two grades of surface form quality that have to be met, and two categories of angular tolerance.

Frequently a prism assembly will be made up of more than one prism and, if there is the possibility of adjustment at the cementing stage to achieve some particular angular relationship, it is important to identify the relaxations that may result for the tolerances on the prism angles during glassworking.

Generally speaking, where some mechanical adjustment at the cementing or mounting stage is possible, prism angles may be worked to an accuracy of ±5 minutes of arc, whereas, in the case of roof angles that split the aperture of the image-forming beams, the angular tolerance will be something like ±5 seconds of arc.

Angular tolerances in the region of ±5 minutes of arc may be achieved when the prisms are blocked in plaster or cemented to machined fixtures, but when roof angles have to be worked to ±5 seconds of arc or better, it is necessary to contact the prisms optically to a reference block that is accurate to the necessary precision.

When prisms have to be made in small quantities it is only necessary for the optical craftsman to be provided with a working drawing of the prism, but when there are large quantities of prisms to be manufactured and the manufacturing stages are to be split up into specialist operations it is necessary to provide detailed instructions for each stage of the manufacturing process. There now follows a series of such detailed instructions for all the common prism forms, from which it is possible to build up specialist instruction for any other prism not specifically mentioned.

1. Porro prism of the first type

The operation layout for the manufacture of this type of prismatic component is given in table 9.1.

This type of prism is common in binoculars, where it erects the image, folds the light path and introduces a stereoscopically beneficial additional separation between the objectives of the twin telescopes. This pattern of binocular prism has been made in more quantities by more manufacturers than any other single prismatic component and many features of its working and tolerancing are characteristic of all prisms.

Operation 1: Issue of material

Generally, small prisms of this type may be manufactured from mouldings prepared from hard crown or medium barium crown glass, but in larger sizes it is usually necessary to avoid inhomogeneity or strain by using slab glass and cutting the blanks from the solid using a diamond saw. There are usually three grades of slab glass: ‘normal’, ‘precision’ and ‘astronomical’, and the additional cost of using precision-grade glass is so high that it is better to try and use normal grade glass and select those pieces that are sufficiently homogeneous and strain free, discarding those pieces that are of inferior quality.

If there is cutting from slab to be done, the edges of the slabs should be ground and polished for inspection and the slabs should then be marked with triangles representing the prisms, care being taken to avoid areas of poor quality.

Operation 2: Cutting glass blocks into plates or prisms

This process has been described in operation 4 of chapter 1, and it is sufficient to say that the slab glass will normally be cut into plates of appropriate thickness and then marked into triangles with a template before being further cut into the prism-shaped pieces.

Operation 3: Parallel grinding of the plates

For the purpose of subsequent processing it is usually convenient to mill or grind the plates parallel in the fashion described in operation 3 of chapter 1.

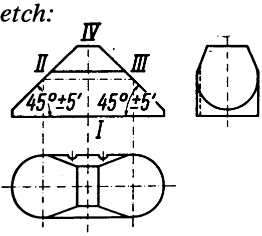
Operation 4: Cementing groups of prisms together for simultaneous working

The individual prismatic pieces are warmed and covered with a high melting point wax before being pressed together in a 90° V-block (in the fashion of operation 6 of chapter 1) with their hypotenuse faces uppermost. The melting point of the wax should be chosen so that any subsequent operation that requires the use of a fixture can make use of a lower melting point wax and therefore leave the stick of prisms undisturbed.

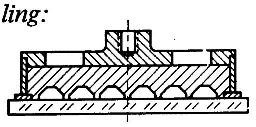
Table 9.1 Operation layout for the manufacture of Porro prisms of the 1st type

Type of job:
Porro prism of the
1st type

Sketch:



Drawing no.:
Tooling:



	Operation	*Process description*
1	Issue of material	Glass type: n_d tolerance: Tolerance for bubbles: Size of pieces: Thickness of pieces: Tolerance for striae:
2	Cut into prisms	Cut the glass block into plates. Plate thickness: Cut the prisms out of the plate according to the template
3	Grind the reference faces parallel	Stick both the reference sides (that is, the sides that are not to be polished) in turn on flat tools, grind them flat and parallel to the specified thickness
4	Stick the prisms into groups	Stick the reference sides of the prisms together to make groups Length of each group:
5	Grind surface I	Grind surface I of the group of prisms by hand, so that it forms a 90° angle with the reference end and check with the angle-measuring device
6	Grind surfaces II and III	Hand-grind surfaces II and III so that they form angles of 45° with surface I, and also an angle of 90° with respect to the reference end of the prisms
7	Grind surface IV	Cement the groups of prisms, with surface I on a flat tool and grind surface IV on a lever-arm machine until the required thickness is reached
8	Decement the groups and clean	Decement the groups from the flat tool and separate the blanks from one another. Clean them in special containers, with an ultrasonic cleaner Cleaning solvent:

Table 9.1 *Continued*

	Operation	*Process description*
9	Mill the blanks to form	Mill the hypotenuse face to the required rounded profile. Mill part of the reference sides at an oblique angle. Mill fixing grooves in the reference side for location in the completed instrument
10	Grind protective chamfers on the sharp corners	Grind protective chamfers on all sides and corners of the prism by hand
11	Block in plaster of Paris for processing surface I	Lay surface I on a flat tool by sliding the moistened surface into position, put the sheet metal ring around the prisms and close it, set the blocking plate over it and pour plaster of Paris through its holes. After the plaster of Paris hardens, separate the block from the flat tool
12	Grind surface I	The grinding of this surface should be restricted to the minimum necessary to obtain a fine ground surface. Type of abrasive: No. of interference rings or spherometer reading:
13	Polish surface I and apply protective lacquer	Type of machine: Type of pitch: Quality of polish appearance: (cosmetic defects allowed) No. of interference rings allowed: Apply protective lacquer
14	Unblock the prisms and block them in plaster of Paris for processing surface II	Loosen the fastenings of the metal ring, remove the plaster of Paris, break the hard plaster disc by hammering, and take out the prisms carefully. For the blocking of surface II, cement auxiliary supporting pieces on surface I, to avoid their tilting in the plaster of Paris when it hardens. Blocking for surface II is the same as described under operation 11
15	Grind surface II	See description in operation 12
16	Polish surface II	See description in operation 13
17	Unblock surface II and block surface III	See description in operation 14

Table 9.1 *Continued*

	Operation	*Process description*
18	Grind surface III	See description in operation 12
19	Polish surface III	See description in operation 13
20	Unblock and clean	See description in operation 14 Cleaning solvent: Ultrasonic cleaning arrangement:
21	Chamfer the prisms	Apply protective chamfer on all the sides by hand
22	Inspect the prisms	Check angles and sizes as per drawing: Check image quality when put in ray path against a test chart, or pin-hole target. Tolerance for appearance defects: Tolerance for bubbles: Tolerance for image quality:
23	Rectify the defective components	Rectify the defects as indicated by the inspector

Operation 5: Grind side I (hypotenuse face)

The hypotenuse face of the stick of prisms is the first surface to be worked and initially it is ground with a relatively coarse abrasive to remove all the chips before being ground with finer grades of abrasive.

The grinding is performed by hand in the usual way on a spinning tool, care being taken to achieve an angle of 90° between the reference end of the stick of prisms and the length of the hypotenuse face. This angle can usefully be checked by standing the stick of prisms on its reference end on a surface plate next to an engineer's square, and examining the air gap between the hypotenuse face and the blade of the square.

Operation 6: Grind sides II and III

The two other sides of the stick of prisms are next worked in the same way, maintaining an angle of 90° with the reference end and an angle of 45° with the hypotenuse face. This grinding is continued until the stick of prisms has the correct cross-sectional dimensions for the next process.

Operation 7: Grind side IV

The height of the prisms is next achieved by cementing several sticks of prisms on a flat surface by their hypotenuse faces and working the tops of the prisms using a lever-arm glassworking machine until the correct height is reached.

Operation 8: Decement sticks of prisms

The prisms are next separated from their backing tool, and then each other, by heating. Before the next operation the prisms are cleaned by soaking in an appropriate organic solvent.

Operation 9: Mill the prisms to the required mechanical profile

Prior to smooth grinding and polishing the optically active faces, it is necessary to bring the prisms to their final mechanical shape and size by milling all the features that have been specified in the design of the instrument for locating the prisms and reducing their bulk.

The features that have to be milled in the specific example we have chosen are shown in the sketch of table 9.1. The first step is to mill the prisms to the required width with the machine shown in figure 9.1. Figures 9.2–9.4 show the above features then being milled. In figure 9.1 the two milling cutters are shown set to the required thickness dimension, and the prisms are fed through this gap mounted around the edge of a circular fixture which is rotated at a rate set by the cutting speed of the diamond milling cutters.

The rounding of the ends of the prism may also be achieved in a continuously driven action and figure 9.2 shows the machine layout for this operation. In this operation and the previous one of milling the prism width, benefit may be gained from providing two pairs of milling cutters, the first of which removes most of the material and the second of which provides a finishing cut.

The milling of the sloping sides of the prism and the location grooves cannot be done with a continuous action, and the rotating fixture has to be indexed in each

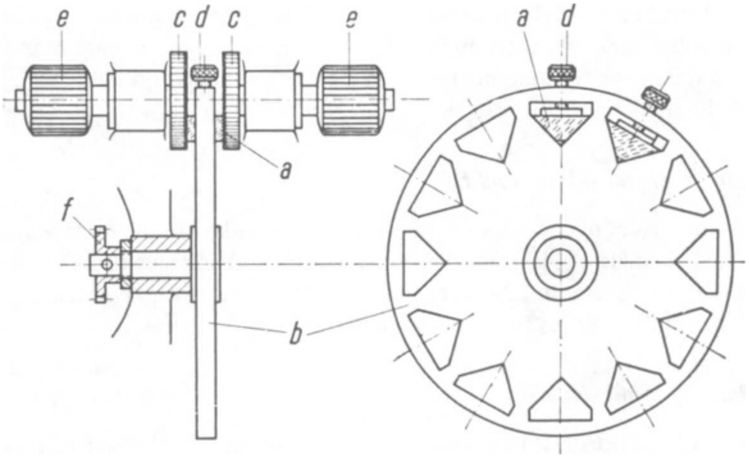


Figure 9.1 Milling the prism width. *a* Prism, *b* rotary fixture, *c* diamond milling tool, *d* clamping screw, *e* milling tool motor drives, *f* rotary fixture drive

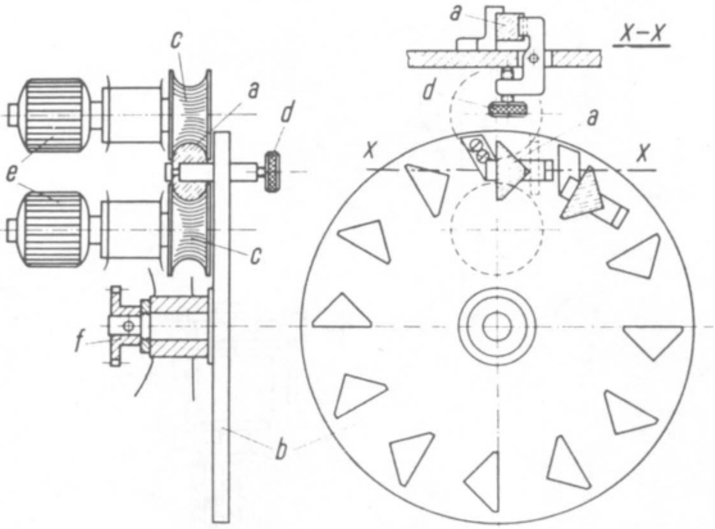


Figure 9.2 Rounding the ends of the prism. *a* Prism, *b* rotary fixture, *c* diamond milling tool, *d* clamping screw, *e* milling tool motor drives, *f* rotary fixture drive

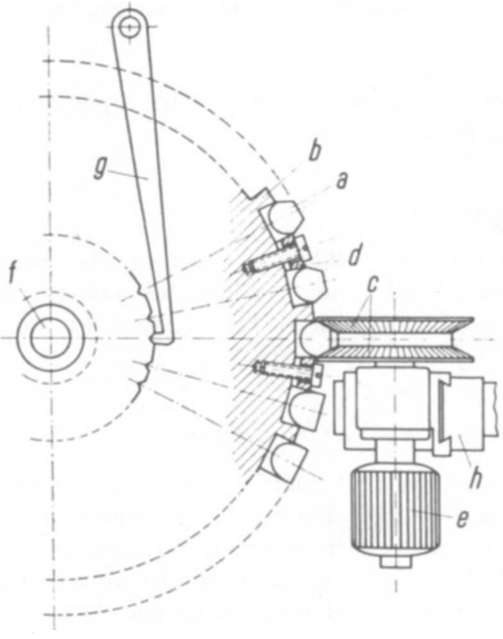


Figure 9.3 Milling the sloping sides of the prism. *a* Prism, *b* rotary fixture, *c* diamond milling tool, *d* clamping plate, *e* motor drive for the milling tool, *f* drive for the rotary fixture, *g* index latch, *h* slide for the feed of the milling cutter

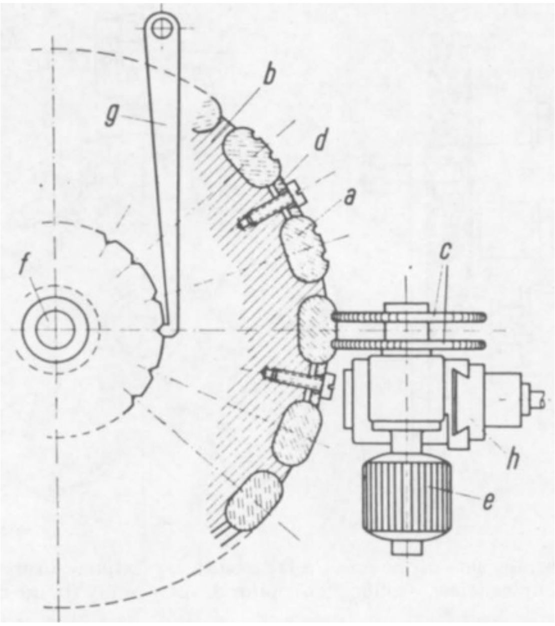


Figure 9.4 Milling of location grooves. *a* Prism, *b* rotary fixture, *c* diamond milling tool, *d* clamping plate, *e* motor drive for the milling tools, *f* drive for the rotary fixture, *g* index latch, *h* slide for the feed of the milling cutter

position and the milling cutters fed to the required depth in each case. Figures 9.3 and 9.4 show these two operations.

Operation 10: Chamfering

Prior to smooth grinding and polishing, all the sharp edges should be chamfered. This operation is best done by hand, care being taken to apply a chamfer that is large enough to survive the smooth grinding operation that follows, and leave the specified chamfer for the completed prism.

Operation 11: Blocking in plaster to work face I

In the tooling sketch of table 9.1 and in figures 9.5 and 9.6 is shown the arrangement whereby the prisms are blocked in plaster of Paris using a true flat surface to locate the prisms before the plaster is cast around them. Just as in the case of lens components, care must be taken to ensure that the prisms seat down cleanly on the datum surface and here it is worth remembering that in the case of prisms there is no process equivalent to edging to true the prism up after polishing, so even a particle of dust 0.03 mm in diameter that can tilt a 20 mm prism face by 5 minutes of arc is a danger.

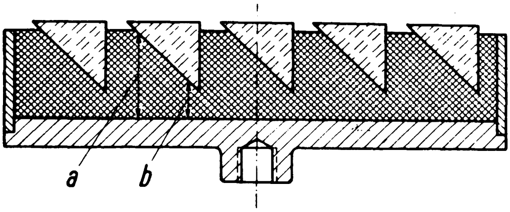


Figure 9.5 Plaster block without guard prisms. *a* Greater thickness of plaster, *b* lesser thickness of plaster

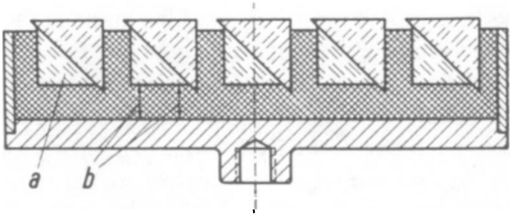


Figure 9.6 Plaster block with guard prisms. *a* Guard prisms, *b* equal thickness of plaster

The prism faces should stand clear of the plaster during working, and to avoid the plaster reaching the datum surface during casting the spaces between the prisms are sprinkled with 2 or 3 mm of sawdust and the sheet metal 'cake tin' is also lifted clear of the datum face with packing pieces before the plaster is poured around the prisms. The gap between the bottom of the sheet metal ring and the datum surface is also filled with wax or plasticine to stop the plaster flowing out.

The plaster of Paris is poured through the holes in the backing plate until it completely covers the prisms. Different types of plaster, mixed to different consistencies, should be tried until a satisfactory result (in terms of strength during working and ease of deblocking) is obtained. Another important factor to bear in mind is the symmetry of the stresses set up in the plaster during setting. Figure 9.5 shows how, when the non-hypotenuse faces of a Porro prism are worked, the inequality of the plaster expansion will tilt the prism when the plaster sets.

Figure 9.6 shows how the symmetry of the prisms may be completed by the use of guard prisms.

Operation 12: Smooth grinding the hypotenuse face

The block of prisms is removed from its datum surface and, if desired, is painted with a water-proof varnish to protect the plaster from the eroding action of the polishing slurry. The block is then worked with an appropriate sequence of abrasives until all the exposed hypotenuse faces are smooth ground.

The choice of the precise form of the fine grinding tool is of some importance. Depending on the dynamics of the polishing machine, so the polisher will require the smooth ground prism surfaces to lie on a slightly concave or convex spherical curve. Normally this curve should be concave so that when polishing starts, the block will grip the polisher at the edges and so proceed in a stable fashion to work from the edge of the block to the centre. The radius of curvature will in any case not be shorter than approximately 300 m, but the precise value for this will be determined by the experience of the polishing craftsman gained with the particular prism concerned.

Operation 13: Polishing the hypotenuse face

Because the radius of curvature of the prism face is more or less infinite it is possible to make up blocks of prisms as big as the polishing machine can handle, and there are clearly significant economic advantages in doing so. Because of this, each individual prism face is only a small proportion of the total polished area, and it is possible to work much closer to the test plate than in the case of most lens components. It is not actually necessary to work particularly close to the test plate in the case of these hypotenuse faces because they are not reflecting faces, but it is often easier to establish a uniform standard of surface form for all prism faces. For reflecting faces it is important to work to an absolute standard of flatness to avoid astigmatism in the reflected wavefronts, and for this reason it is usual to work all prism faces to 'colour' or 'white band' quality.

When the block of prisms is completely polished the exposed prism surfaces are lacquered to protect them from the alkaline etching effect of the plaster when they are turned round for working the other faces.

Operation 14: Deblocking and reblocking

The block of prisms is broken down by undoing the threaded clasps of the 'cake tin' skirt and breaking the plaster of Paris lump down into smaller pieces, so releasing the prisms.

The symmetry of the prism is next completed by waxing a series of dummy prisms on to the hypotenuse faces as described under operation 11, and the next face to be worked is carefully cleaned prior to laying the symmetrical double prisms down on a datum flat.

The reblocking operation is exactly the same as described under operation 11.

Operations 15–19

These are exactly the same as operations 11–14 in the process schedule given in table 9.1.

Operation 20: Removal of plaster and final cleaning

When the third side of the prism is finish polished the plaster block is broken down again and the prisms are soaked in a suitable organic solvent to remove all traces of plaster of Paris, lacquer and polishing rouge. Any persistent traces of rouge stain or lacquer may need to be removed with a hardwood scraper, used in conjunction with an organic solvent.

Operation 21: Inspection and rectification of chamfers

The residual chamfers on all edges should next be examined for conformity with drawing and any that have been removed or significantly reduced by the smooth grinding and polishing should be replaced by hand grinding.

Operation 22: Testing

The testing of prismatic optical components is more complicated than inspecting lens components, because there are more sensitive features and a generally greater potential for error than in the case of lenses.

The features that must be inspected either on a sample basis, or for every prism as appropriate, are as follows:

(i) Material quality – bubbles, striae, stress.
(ii) Surface form.
(iii) Meridional and pyramidal angles.
(iv) Linear dimensions.
(v) Cosmetic quality – scratches, sleeks, chips and stains.

As far as the optical performance is concerned, by far the best testing procedure is to use a Twyman-Green interferometer to measure the departures from flatness of a wavefront that has been transmitted through the prism. Once the interferometer has been set, this test can be very quick, requiring only a few moments to place each prism on the interferometer and adjust and view the interference pattern formed through the prism. The interferometer required for this checking need not have an aperture larger than the diameter of the optical pathway through the prism, and if its mirror rotations are calibrated it may also be used to check simultaneously the angular deviations introduced by the prism.

Even if a Twyman-Green interferometer is available, it will not usually have calibrated mirror rotations, and it is more common to check the angular errors of the prisms using an autocollimator or an equivalent optical projection lever that magnifies the angular errors and displays them as the departure of the image of a crosswire graticule from a calibrated reference position. In both cases the meridional and pyramidal errors cause displacements in perpendicular directions and it is obvious which is the predominant error. Pyramidal error is that error that results from the prism not being of uniform triangular cross-section, that is, slightly pyramidal rather than perfectly prismatic. Meridional errors are those angular errors that affect the two angles of 45° or the angle of 90°.

The most important angular features to check are the meridional angle of 90° and the pyramidal error, because it is errors in these two features that introduce deviations in the line of sight in the finished instrument, and which therefore have to be compensated for as the instrument is built. A useful and easily applied test for these two features consists of laying a row of finished prisms on their hypotenuse faces so that they bridge a slot that exposes most of their hypotenuse faces below, and then viewing a reflection of one's own eye via a 45° mirror mounted below the slot. A prism whose angle of 90° is correct will present a circular image of the pupil of one's eye, but any error in that angle will split the image into two and show either a 'cats eye' shape or the sort of shape that is usually associated with the field of view of a pair of binoculars. The pyramidal errors show up as unevenness in the spacing of the reflected pupil images. This test is useful for the rapid sorting of a large numbers of prisms, but it is not easily made quantitative.

Operation 23: Rectification of prisms by hand working

Most errors detected at the inspection stage may be rectified by judicious hand working. Particularly, cosmetic surface defects may be removed by polishing, or smooth grinding and polishing, and this applies also to errors of surface form, and angular defects.

A particular problem that arises in the hand polishing of individual prisms is the high standard of surface form that is required and, while this is not too much of a problem when large blocks of prisms are being processed, it requires particularly painstaking working methods when the prisms are worked individually. Precautions must be taken to avoid the transmission of the heat of the hand to the prism during polishing, otherwise the prism will be thermally distorted, so nullifying the care that is lavished on the surface form quality. The best way of achieving this last requirement is to hold the prism in a wooden clamp and touch only the clamp and not the prism. Women take to this work of hand correction particularly well.

The surface curvature error tolerances on the reflective faces of prisms are sometimes as tight as 0.1 interference bands, and the corrective polishing work must proceed with frequent flattening of the pitch polisher on a master surface. The master surface may be metal or granite and it is usual to work with two polishers, one of which is in use and one of which is lying in contact with the master surface for flattening.

If the surface form of the prisms is in error it is necessary to use a relatively hard pitch polisher, whereas if the defects are only cosmetic a relatively soft pitch polisher should be used. To achieve simultaneous correction of surface form and cosmetic quality it is necessary to use rapid and uniform polishing strokes, and the surface of the polisher should be reticulated into many small facets to accommodate itself to the characteristics of hand polishing.

When a block of prisms or lenses is polished the contact pressure is more even than is possible with the hand polishing of individual components, and the polisher facet size may be larger, but for the hand working of prisms the requirements of forming the polishing layer rapidly and maintaining the localised humidity at the required level lead to the use of small polisher facets. These facets are formed by pressing an open weave cloth into the surface of the polisher or, alternatively, a plastic mesh may be used. When the correct sized facets are formed and the correct pitch hardness has been used with the correct rouge and water mixture, it is found that the polishing crust forms quickly and the prisms move smoothly over the polisher without being sucked into contact and digging their edges in, so allowing a regular and well-controlled polishing action.

Where a large number of prisms of one type are in need of rectification it is often more economic to block them up in plaster of paris, and work them in the usual way, but is not possible to do this for polishing alone, because of the impossibility of maintaining the prisms in perfect superficial contact with the master surface during blocking.

Although traditionally prisms have been made of hard crown or medium barium crown glass, there are now requirements for prisms made of glasses with higher refractive indices, particularly for television chromatic beam splitters, and the working of these glasses places heavy demands on the glassworkers if they are to achieve simultaneous surface form and cosmetic quality.

Figure 9.7 shows a fixture that may be used for the corrective polishing of prisms by machine. This is particularly suitable for the transmitting faces of prisms, where the surface form requirements are not as demanding as for reflecting faces. The cycle time for this technique may be approximately 3 minutes, and if soft pitch is used the surface of the prism corrects the pitch shape rather than the other way around, so leaving the surface shape of the prism undisturbed but having removed stains and other superficial blemishes.

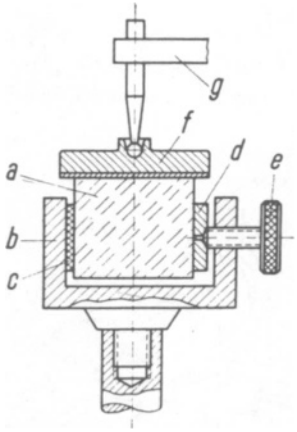


Figure 9.7 Fixture for holding prisms while they are polished during rectification. *a* Prism, *b* fixture to be attached to the work spindle of the lever-arm machine, *c* cork packing, *d* pressure pad, *e* clamp screw, *f* polishing tool, *g* lever arm of the polishing machine

Manufacture of Porro prisms of the first type from moulds

Considerable economies are possible if Porro prisms can be manufactured from moulds. In particular it may be possible to work only the three active optical faces, leaving the triangular faces unworked. It may also be possible to avoid blocking in plaster of Paris by the use of metal fixtures into which the prisms are held by wax.

Although the greatest economy in glass processing is achieved by not working either of the triangular faces, it is often preferable to work one of these faces as a datum, both for subsequent glassworking and for mounting in the binocular body (see figure 9.8), and in this case it is sensible to mill this face first and then work each of the optical surfaces so that they are perpendicular to that datum face to within ±5 minutes of arc.

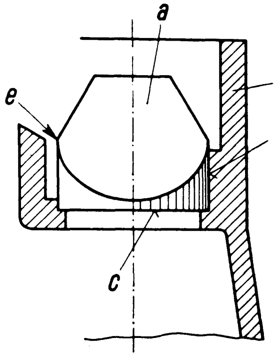


Figure 9.8 Seating of a Porro prism in a binocular body. *a* Prism, *b* binocular body, *c* datum shelf, *d* datum wall, *e* direction of clamping forces

To take advantage of the economies offered by mass production it is necessary to provide specialist fixtures for each stage of the glass processing, so that several prisms may be worked simultaneously. Figures 9.9 and 9.10 show the details of a

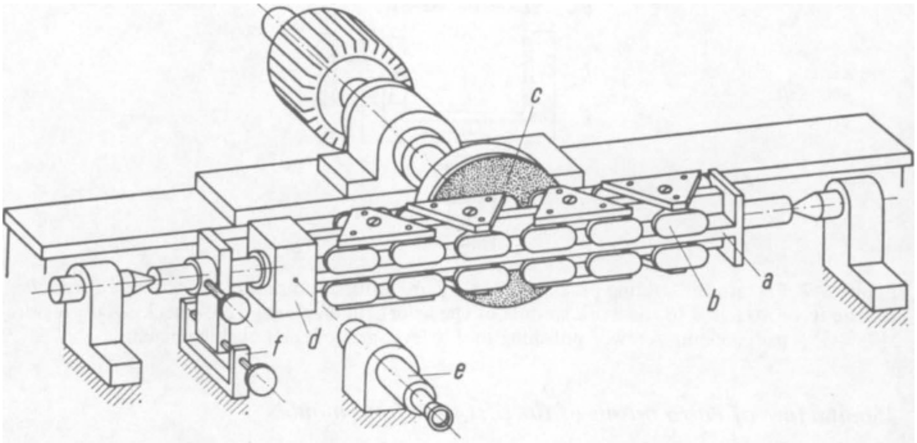


Figure 9.9 Mandrel fixture for milling the hypotenuse faces. *a* Fixture, *b* prisms, *c* diamond milling cutter, *d* master block, *e* autocollimator, *f* fine adjustment for mandrel rotation

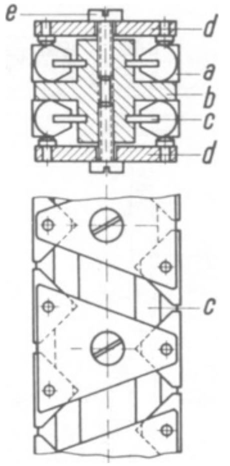


Figure 9.10 Details of the clamping arrangement for the fixture used to mill the hypotenuse faces. *a* Prism, *b* datum shelf of the fixture, against which the triangular datum faces of the prisms locate, *c* strip 'cage' for locating prisms, *d* clamp plate, *e* clamp screw

fixture that is used for milling the hypotenuse faces, using the reference triangular faces as datums. The prisms are arranged around a mandrel that also carries a reference block, so that the mandrel may be rotated by precisely 90° if the autocollimator reflections from the reference block are used to make each setting.

Once the prisms are mounted in the fashion shown in figures 9.9 and 9.10 and the mandrel is set to one of its four positions, either the milling head or the table carrying the fixture is traversed to grind the faces of the row of prisms.

The full advantage of these fixtures lies in their application to all stages of the surface processing. When the milling is finished, several mandrel assemblies may be mounted in a frame to form a block, as shown in figure 9.11. After smooth grinding, this same fixture assembly holds the prisms while they are polished. During both these operations the prism mandrel is constrained from rotating by a supporting plate which has been machined flat and parallel to a thickness that holds the spindles of the fixtures in the parallel section of the location notches shown at *b* in figure 9.11 and provides a datum surface against which to measure stock removal and the parallelism of the mandrel assemblies.

After the hypotenuse faces of the prisms have been polished, the 90° faces are processed in a similar fashion, using mandrel fixtures of the type shown in figures 9.12 and 9.13.

As the hypotenuse faces of the prisms that are loaded in the fixture of figure 9.12 have already been polished, great care must be taken to protect these faces while the 90° faces are worked, and a suitable shim material must be used between the prisms and the fixture. Shim materials that have been used with success are paper and celluloid, but whatever material is used it must be cleaned very carefully to avoid scratching the hypotenuse faces.

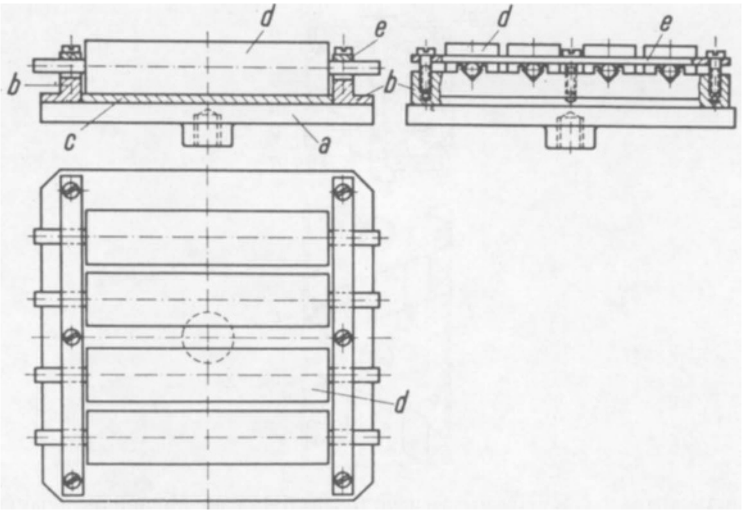


Figure 9.11 Smooth grinding and polishing block made up with four processing mandrels. *a* Base plate, *b* location pieces, *c* supporting plate, *d* mandrel fixture with prisms, *e* clamping bridge strips

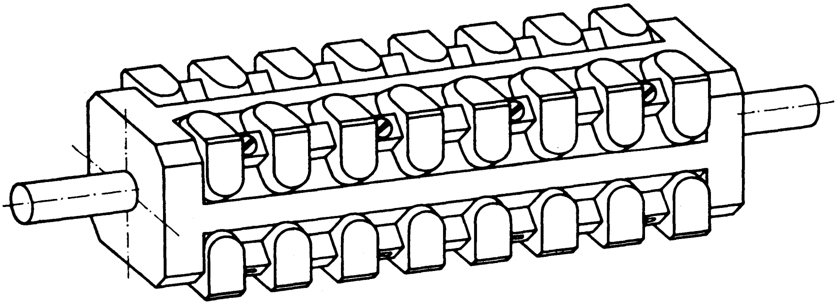


Figure 9.12 Mandrel fixture for processing the 90° faces of the Porro prism

The location of prisms in the mandrel fixture is designed to simulate the same feature of the mounting in the binoculars (figure 9.8) and it is this use of common manufacturing and mounting datums, and the precision of the 90° angle that is generated, that are the cornerstones of successful binocular assembly.

The processing of the 90° faces proceeds next in exactly the same fashion as that of the hypotenuse faces, using the same tools and fixtures as before.

Manufacture of Porro prisms by cementing them on supporting jigs

Another method of manufacturing Porro prisms which has significant economic advantages over plaster blocking is to work a number of prisms simultaneously by cementing them to precisely machined jigs.

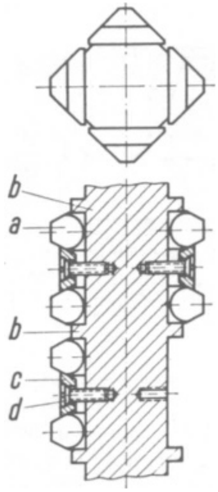


Figure 9.13 Clamping arrangement for the fixture shown in figure 9.12. *a* Prism, *b* datum fence against which the reference face of the prism locates, *c* clamping plate, *d* clamping screw

The procedures of working with jigs of this type vary in detail, but the usual scheme consists of first smooth grinding and polishing the hypotenuse faces using conventional plaster blocking, and then mounting the prisms on jigs in the fashion shown in figures 9.14 and 9.15, care being taken as before to avoid scratching the hypotenuse faces.

The cementing of the prisms to their 90° jigs should make use of the same prism datums as the binocular mounting seat, as in the case of the previous method, and including the chamfer at the toe of one of the 45° faces, which is used to locate against the fence of the fixture shown in figure 9.15.

The processing of the prisms mounted on their 90° jigs consists of fine grinding and polishing each of the two faces to a standard dimension from the datum face of the base plate, and in this way a prism of the required dimensions is generated in a straightforward fashion.

The 90° angle that is produced on the prism is a direct reproduction of the 90° angle of the jig, so it is as important to control the manufacture of the jigs to appropriate tolerances, and also to maintain the cleanliness of the datum faces, as it is to avoid any bruising of them during use.

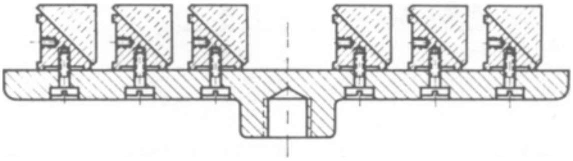


Figure 9.14 Metallic angular jigs holding the prisms mounted on a flat base plate

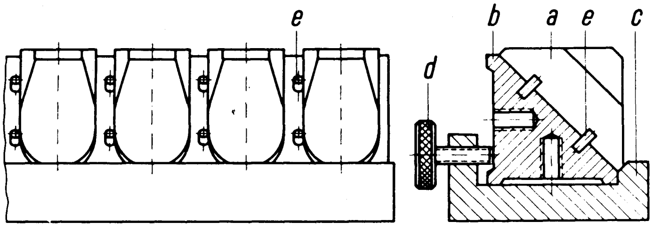


Figure 9.15 Fixture for aligning the Porro prisms while cementing them on the 90° jigs. *a* Prism, *b* 90° jig, *c* fixture for aligning the prisms while cementing, *d* clamp screw, *e* datum pins for aligning the reference face of the prisms

2. Dove prisms

As far as manufacturing geometry is concerned the Dove prism resembles a truncated Porro prism, but the polished faces are used in a different fashion, as is shown in figure 9.16. The long hypotenuse face is now used as a mirror, and where previously it was the 90° faces that had to be polished with particular attention to surface curvature, it is now the hypotenuse face that must be polished to especially high

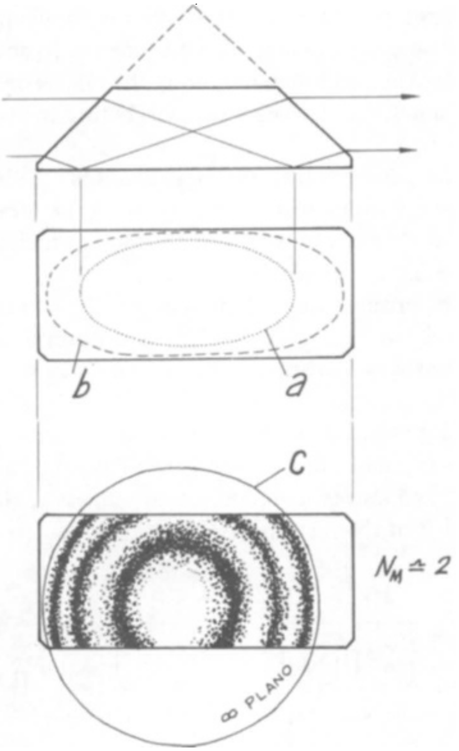


Figure 9.16 Dove prism showing ray paths and test region of hypotenuse face. *a* Characteristic test region, *b* total area used, *c* test plate

standards of absolute surface flatness. Not only is the hypotenuse face now a reflector, but the angle of incidence of the optical axis is greater than the 45° encountered in the Porro prism, and is given by

$$i = 45^\circ + \sin^{-1}(1/n\sqrt{2})$$

where n is the refractive index of the glass of the prism.
If $n = 1.6$ (say) then

$$i = 71.2^\circ$$

The astigmatism introduced by any lack of flatness is given in terms of wavelength by the equation

$$\text{astigmatism} = (N_\mathrm{M} - N_\mathrm{S})n\lambda \cos i$$

where λ is the wavelength of the light, N_M is the number of Newton's test plate ring fringes along the characteristic elliptical hypotenuse test region and N_S is the number of fringes across the hypotenuse test region (the test region is taken to be the elliptical patch illuminated by any single object point (see figure 9.16)). If we now take as an example the case where the hypotenuse face is simply spherical, showing say two circular Newton's ring fringes along the major axis of the characteristic elliptical test region, then the number of ring fringes across the minor axis of the test region will be given by

$$N_\mathrm{S} = N_\mathrm{M} \cos^2 i$$

where, in this case $N_\mathrm{M} = 2$ and $i = 71.2^\circ$, so that $N_\mathrm{S} = 0.21$ ring fringes, and the astigmatism will be

$$\text{wavefront astigmatism} = (N_\mathrm{M} - N_\mathrm{S})n\lambda \cos i = 0.9\lambda$$

Bearing in mind that a standard wavefront aberration tolerance may be taken as approximately 0.25λ, we can see that in this case the very modest error of two Newton's fringes along the major axis of the test region, which would be quite acceptable for a lens, has been scaled up to an unacceptable level of astigmatism by the large angle of incidence at the reflecting face.

So how good must these Dove prism hypotenuse faces be? If we can tolerate 0.25λ of astigmatism, and if we assume the fringes on the hypotenuse face are circular, we can set

$$N_\mathrm{M}(1 - \cos^2 i)n\lambda \cos i = 0.25\lambda$$

and thus

$$N_\mathrm{M} = 0.54 \text{ fringes}$$

that is, approximately half a fringe of absolute flatness.

There are two important considerations here. First, the equation for astigmatism takes the difference between N_M and N_S, so if the hypotenuse faces are worked so that the fringes are elliptical to the extent that

$$N_M = N_S$$

then there will be no astigmatism introduced however many fringes there are. In practice it is not usually feasible to work these faces in this way, especially in the case of the Dove prism where $i = 71.2^\circ$ and the elliptical test region has a ratio of major to minor axis of approximately 3:1, but it points to the way the surfaces should be assessed when they are test plated – assuming that the surface is nearly flat and that the test plate has been put on clean. When one presses on the test plate at the end of the hypotenuse face, to produce fringes running parallel to the minor axis of the elliptical test region, the fringes revealed should be more curved than the fringes that are revealed when the edge of the test plate at the end of the minor axis is pressed (as long as the surface is similarly either concave or convex along both the major and minor axes).

Second, if the instrument into which the prism is to be fitted is so designed that the beams passing through the prism are of small cross-section, the characteristic elliptical test region becomes small and one only has to work the sensitive face to half a fringe over that reduced area. In this case, if the characteristic test region only fills one-quarter of the length of the hypotenuse, the whole hypotenuse face may exhibit as many as

$$0.5 \times 4^2 = 8 \text{ fringes}$$

which, of course, is easy to achieve on prisms of the normal size.

The Dove prism can be manufactured using the same schedule of operations as the Porro prism of the first type.

As in the case of the Porro prism of the first type the hypotenuse faces may be worked with the prisms cemented together as a stick, so avoiding plaster of Paris blocking if the other faces are worked using specialised fixtures.

As shown in figure 9.17 the fixtures are usually designed to operate on standard lever-arm glassworking machines. The angular tolerances on the central prismatic support piece and the intermediate spacers directly affect the angles of the prisms that are manufactured, so the metallic datum faces must be cut with due attention to the precision of their angles. Any systematic error in the angles of these jig pieces may be nullified if opposite ends of each prism are blocked on opposite sides of the fixture, so preserving the all important 90° prism angle, even if the 45° angles are in error. This last refinement of operational procedure is not usually necessary, but conscientious craftsmen may choose to work in that way as a matter of personal preference if they are told about its advantages.

3. Porro prisms of the second type

The operational schedule is given in table 9.2

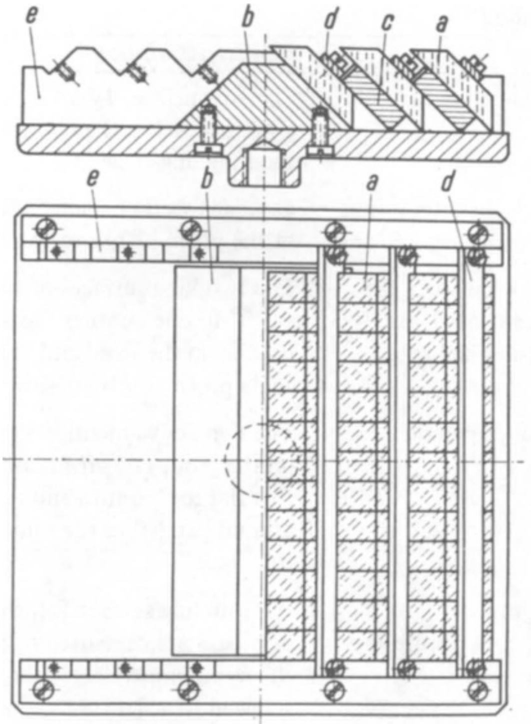
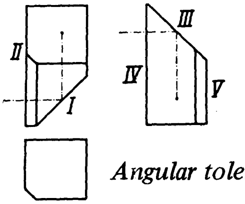


Figure 9.17 Special fixture for holding Dove prisms during processing. *a* Prism, *b* prism support core, *c* intermediate plate, *d* clamp strip, *e* clamp strip support

Table 9.2 Operation layout for manufacture of Porro prisms of the 2nd type

Type of job:
Porro prism of the 2nd type

Sketch:



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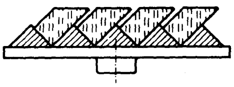
Tooling:



Angular tolerance ± 5′

Operation	*Process description*
1 Issue of material	Similar to the description of operation 1 in table 9.1
2 Cut the glass into pieces	Similar to the description of operation 2 in table 9.1 except that the blanks produced are cuboidal and not triangular

Table 9.2 *Continued*

	Operation	*Process description*
3	Grind prism faces parallel	Cement surfaces IV and V on a flat tool and grind parallel to the required dimensions for the roughing stage
4	Stick prism blanks into groups	Cement together the parallel ground faces of the prism blanks to form groups
5	Grind the angle between the faces of the cemented groups of prism blanks	The two long surfaces of the groups that are at 90° to one another should be ground while holding in the hand and checked with an angle protractor by observing the light gap
6	Grind the groups parallel	The two above-mentioned surfaces ground on the groups of prisms are each cemented to a flat tool in turn and the opposite sides ground parallel to the dimensions required at this stage
7	Cement the groups of prisms to the tool fixture and grind surface I	For grinding surface I, the cuboidal groups of prisms are cemented to the 45° strips, the hypotenuse side of the strips being screwed to a flat tool, close to one another such that they form an angle of 90° between them, and then the groups of prisms are cemented into this 90° angle between the strips (see the tooling diagram at the top of the table 9.2). Surface I is ground and fine ground at 45° to surface II according to the dimensions necessary at this stage
8	Polish surface I	Similar to operation 13 in table 9.1
9	Remove the prisms from the tooling fixture	Take the groups of prisms from the strips by heating, taking care to warm only to the extent necessary to decement them from the strips, and in this way the blanks themselves that form the individual prisms do not get displaced with respect to one another
10	Embed in plaster of Paris for the processing of surface II	Similar to operation 11 in table 9.1
11	Grind surface II	Similar to operation 12 in table 9.1
12	Polish surface II	Similar to operation 13 in table 9.1

Table 9.2 *Continued*

	Operation	*Process description*
13	Take the prisms from the plaster of Paris, decement the groups of prisms and clean	Unscrew the sheet metal ring and take off the blocking body plate. Break the plaster of Paris disc and take out the prism groups. Heat the groups of prisms to decement them and separate the individual prisms. Clean the prisms in special containers or in an ultrasonic arrangement. Cleaning solvents:
14	Apply protective lacquer and block cement them for chamfer	Paint the polished side with protective lacquer, cement the prisms into the fixture (similar to operation 7) and grind the chamfers on the edges, as specified in the drawing
15	Decement the prisms from the fixture and clean	Decement the prisms from the fixture strips. Cleaning solvent:
16	Apply protective lacquer and embed in plaster of Paris for the processing of surface III	Paint protective lacquer on the polished faces and embed the prisms in plaster of Paris. The prisms are blocked up with the usual moistened contact, in a fixture that is similar to the one used in operation 7: the sheet metal ring is put around them, the blocking plate is placed over the top and plaster of Paris is poured through the backing plate. After the plaster of Paris has hardened, the tooling strips are removed
17	Grind surface III	The faces projecting out of the plaster of Paris are next ground with rough emery until flat surfaces are formed, and then with medium and fine emery until the desired size and smoothness of the surfaces is obtained
18	Polish surface III	Similar to operation 13 in table 9.1
19	Unblock, take the prisms out of the plaster of Paris and clean	Similar to operation 14 in table 9.1. As there, an ultrasonic cleaner is a useful aid. Cleaning solvent:
20	Chamfer	Grind protecting chamfers on all edges and corners as per drawing dimensions

Table 9.2 *Continued*

	Operation	*Process description*
21	Apply protective lacquer and embed in a plaster of Paris block for the processing of surface IV	Paint protective lacquer on the polished surfaces, otherwise this operation is similar to operation 11 in table 9.1
22	Grind surface IV	Similar to operation 12 in table 9.1
23	Polish surface IV	Similar to operation 13 in table 9.1
24	Unblock and remove the prisms from the plaster of Paris.	Similar to operation 14 in table 9.1
	Clean	Cleaning solvent: Ultrasonic arrangement:
25	Inspection of prisms	Similar to operation 22 in table 9.1
26	Rectification of prisms	Rectify the defects indicated by the inspector
27	Cementing the prisms together	Surfaces II of each pair of Porro prisms of the 2nd type are cemented together so that their surfaces I are set at 90° to one another, forming an erecting prism. Type of cement used: For stability of holding them together, surfaces IV and V may be cemented with protective cover plates. The grey surfaces of the prism should be painted black. Type of paint to be used: While the prisms are being cemented together, the erecting prism combination is placed in the ray path between a collimator and a telescope, and before the cement hardens the two prisms are rotated and adjusted with respect to one another. After the cement has hardened they are checked again to ensure that the image rotation is 90° and that the line of sight is displaced to the correct position without angular deviation

Operations 1 and 2: Issue of material and initial cutting to shape

These operations are the same as described under Porro prisms of the first type.

Operation 3: Grinding plates parallel

This operation is the same as described under Porro prisms of the first type.

Operation 4: Cementing prisms into groups

This operation is the same as described under Porro prisms of the first type.

Operation 5: Grinding two datum faces at 90°

Two adjacent faces of the stick of prisms are ground so that they are at 90° to each other. This grinding is done by hand on a spinning circular tool until the two datum faces are smooth and free of chips, and the 90° angle is better than 5 minutes of arc, as checked with an engineer's square. The tolerance of 5 minutes of arc corresponds to a gap between the square and the prism face of 0.03 mm in every 20 mm.

Operation 6: Grinding sticks of prisms parallel

The datum faces are next used to grind the sticks of prisms parallel. The datum faces are cemented in turn to a flat blocking tool, and the opposite faces are ground until the whole block has 'cleaned up' and the surface texture is uniform and of the correct degree of smoothness.

Operation 7: Cementing the sticks of prisms in the fixture for grinding and polishing (illustrated at the top of table 9.2)

Low melting point wax is used to cement the strips of prisms to the accurate jig blocks on the flat tool that acts as a datum surface. Low melting point wax is chosen so that the strips of prisms will remain together when they are initially deblocked.

The jig blocks are made of steel with carefully machined angles, and the wax is made from paraffin wax and rosin, the proportions being adjusted to suit the particular job that is on hand.

This operation generates the 45° angles, and the length of the prisms is controlled by measuring the depth to the datum face, where patches are left clear of wax so that the tip of a depth micrometer can locate against the flat surface of the backing tool and thus check the parallelism of the worked face with respect to the datum.

Operation 8: Polishing the first side

This is just the same as the polishing process for plaster of Paris blocks of Porro prisms of the first type.

Operation 9: Deblocking prisms from the fixture

The base plate of the block is carefully heated until it is possible to remove the strips of prisms from the fixture without separating the individual prisms.

Operations 10–12: Forming a plaster of Paris block and grinding and polishing surface II of the prisms

This operation is similar to that described for Porro prisms of the first type.

Operation 13: Deblocking

The plaster of Paris block is broken down and the sticks of prisms heated to separate the individual prisms. Finally the prisms are soaked in an organic solvent such as trichlorethylene to remove all traces of lacquer, plaster of Paris and rouge.

Operation 14: Blocking the prisms to grind the chamfer

The polished faces are lacquered before the prisms are wax-cemented to 90° V-blocks, located on a flat datum tool. The chamfer is applied in the usual way and parallelism is maintained between the worked surface and the datum blocking surface.

Operation 15: Decementing the prisms from the 90° jigs

For this operation the 90° jigs are heated to release the prisms, which are then cleaned in the usual way, prior to relacquering the polished faces.

Operation 16: Blocking in plaster of Paris for processing face III

Face III of these prisms is processed in a similar way to face I, and the tooling is the same as that illustrated at the top of table 9.2.

The cleaned and lacquered prisms are located in the V-blocks by the as yet unworked prismatic part of each prism which has to be removed to form face III. The V-blocks holding the prisms are located on a flat tool as a datum, and the whole assembly is surrounded by a ‘cake tin’ skirt of sheet metal, which rests in a ring of plasticine to stop the plaster of Paris pouring away when it is cast. A backing plate with holes is placed over the ‘cake tin’ fence and the plaster of Paris is poured through these holes to form the block. As with all plaster blocking there is the possibility of the prisms tilting as the plaster sets and, if the angular tolerances require it, the symmetry of the prisms may be completed by cementing a dummy prism on to the already worked faces of the prisms, prior to making the block.

When the plaster has set, the prismatic jig bars and pieces of plasticine are removed, leaving the face of the block as a series of prismatic protrusions which must next be ground or milled away.

The plaster surface is trimmed and, if preferred, lacquered before the next process.

Operation 17: Rough grinding surface III

The processes described here are appropriate to small prisms, where it is feasible to remove large quantities of glass using loose abrasives. However, in the case of large prisms these two steps would be replaced by blocking on a flat tool, made possible by the purchase of glass blanks that already have surface III moulded.

The prisms are now milled or worked with coarse abrasives to remove the roof-shaped pieces of glass on the face of the block; grinding continues with finer abrasives until the chamfer at the 45° edge just remains. This maintenance of the chamfer at the 45° edge avoids the formation of chips.

The final, finest abrasive must be used to form a surface on the block that has the required slightly concave or convex curvature (as necessary) to match the characteristics of the polishing process.

Operations 18 and 19: Polishing surface III and deblocking

These operations are similar to those described under operations 12 and 13.

Operation 20: Grinding of chamfers

All the sharp corners are next chamfered by hand on a spinning tool using a medium grade of emery, as previously described for the Porro prism of the first type.

Operations 21–24: Blocking, grinding and polishing surface IV followed by deblocking

These operations are similar to those described for the Porro prism of the first type.

Operations 25 and 26: Inspection and rectification

This work is performed in the same way as the corresponding operations on the Porro prism of the first type.

Operation 27: Cementing the prisms together

Although different designs of Porro prism binocular telescope are assembled in different ways, the most common arrangements are Porro prisms of the first type which are not cemented, and Porro prisms of the second type which are permanently cemented. The advantages of a cemented prism are a fixed 180° image erection rotation, a stable, aligned mechanical assembly and an improvement in transmission.

The cementing is achieved with one prism held in a clamp and the other prism adjusted with respect to it, to set the image rotation at 180° and the exit line of sight parallel to the input line of sight at the correct position.

The optical cement used must be selected to meet the necessary environmental specification, but the most convenient cement to use is the ultraviolet setting type, which may be set very quickly by the action of ultraviolet radiation once the necessary adjustments have been made.

The image-rotation setting is achieved by viewing a vertical datum line through the prism with a telescope that has a vertical datum line or datum lines in its focal plane. This arrangement is best implemented by setting up a nylon monofilament plumb line in front of the prism and viewing it through the prism assembly with a telescope provided with a double vertical line graticule in the eyepiece plane representing the tolerance on the verticality of the image.

If additional strength of prism bonding is required, metallic plates may be cemented over the cement joints where they emerge on ground faces. These same plates may be used as mechanical datums to attach the prisms to the binocular telescope body, in which case the positioning of the metallic plates must be controlled so that their datum features are in the correct position with respect to the reflecting faces.

4. Pentagonal Prisms

These prisms deviate a line of sight by precisely 90°, irrespective of the attitude of the prism, and this property is used in the rangefinder and a number of other surveying and metrological instruments, in addition to its application as an ocular prism for single-lens reflex cameras.

The cross-sectional shape of these prisms is shown in the diagrams at the top of tables 9.3 and 9.4 and, depending on the application, these prisms may be worked with interfacial angular tolerances of ±5 minutes of arc for ocular applications, ±1 minute of arc for survey sweep squares, or ±5 seconds of arc if they are required for rangefinding or metrological situations.

Pyramidal errors in these prisms introduce a deviation in the line of sight, so it is normal to work with pyramidal error tolerances of the same magnitude as the tolerances on the meridian angles.

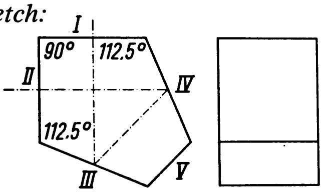
Pentagonal prisms of 5 minutes of angular accuracy

Different angular tolerances dictate different manufacturing methods, and table 9.3 describes the schedule of operations required to manufacture pentagonal prisms to an angular accuracy of 5 minutes of arc.

Table 9.3 Operation layout for the manufacture of pentagonal prisms (angular tolerance ±5 minutes of arc)

Type of job:
pentagonal prism
(±5′)

Sketch:



Angular tolerance ±5′

Drawing no.:

	Operation	*Process description*
1	Issue of material	See table 9.1, operation 1
2	Cut glass into prisms	See table 9.1, operation 2
3	Grind prism faces parallel	See table 9.1, operation 3
4	Stick prism blanks into groups	See table 9.1, operation 4
5	Grind surfaces I and II	Grind surfaces I and II at 90° ±3′ to one another by hand and also ensure that these surfaces are at 90° to the reference side, which is not to be polished
6	Grind surfaces III and IV	Grind surface III with respect to surface II at an angle of 112.5°; surface IV to surface I at an angle of 112.5° by hand, and check by light gap. Also ensure that, in doing so, the surfaces are at 90° with respect to the reference side and that surfaces III and IV form an angle of 45° with each other
7	Grind surface V	See table 9.2, operation 7
8	Embed the prisms in plaster of Paris in turn, for working surfaces I–IV, grind, polish and unblock in each case	The surfaces are to be processed one after another See table 9.1, operations 11–14
9	Decement groups of prisms and clean them	See table 9.1, operation 8
10	Chamfer the edges	See table 9.1, operation 21
11	Inspection	See table 9.1, operation 22
12	Rectification	See table 9.1, operation 23
13	Silvering	Complete the silvering and coppering of the prisms and apply protective lacquer in accordance with the specification
14	Final inspection	To be done as per drawing specification

The operations listed in table 9.3 are each similar to the corresponding operations performed on Porro prisms of the first type, bearing in mind the differences in the angles of the prism.

The operations of silvering, coppering and protective lacquering are the same as described in chapter 7 on the manufacture of curved mirrors.

Pentagonal prisms of higher angular accuracy

The technique outlined in the previous section may be extended, in a modified form, to approximately 2 minutes of arc angular accuracy, but below that level of error it is necessary to adopt different techniques, with the aim of avoiding, or at least minimising, any hand work that may be necessary.

When the angular tolerances approach a few seconds of arc the prisms are best worked while they are optically contacted on to master angle blocks. This technique effectively enables the craftsman to copy the master angle on to the new prism to within a few seconds of arc.

In the case of prisms with angular tolerance at about 2 minutes of arc the operations numbered 5–7 in table 9.3 are replaced by the copy milling method illustrated in figure 9.18, as has been applied to Porro prisms of the first type manufactured from mouldings. In the case of Porro prisms, each individual moulding is clamped in a seating, whereas in the case of pentagonal prisms, a group of moulds which have been milled parallel are cemented together with centres set on the end faces with the aid of a fixture (to achieve alignment between them). The master prism is also mounted on the same spindle for the purpose of copying its angles on to the stick of prisms.

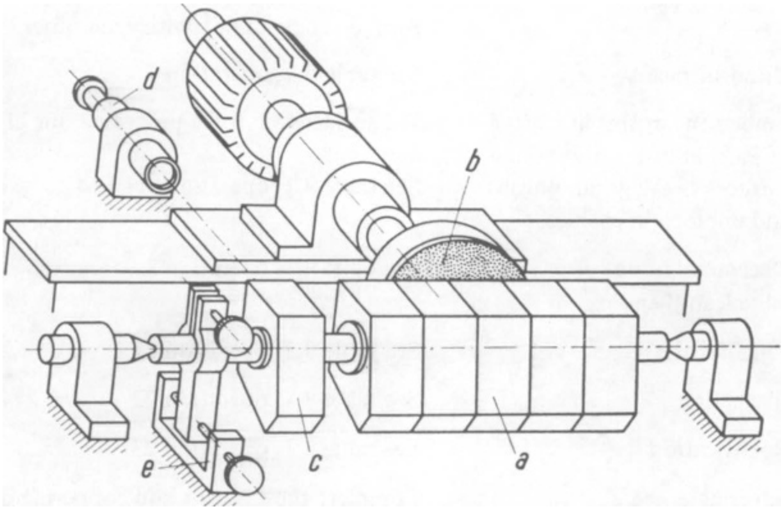


Figure 9.18 Schematic arrangement of a milling machine for rough grinding pentagonal prisms by copying a master sample. *a* Strip of prisms clamped between centres, *b* diamond tool, *c* template prism, *d* autocollimator, *e* angular adjustment

Prisms milled in this fashion and then smooth ground and polished in plaster blocks can be worked to the required tolerance of ±2 minutes of arc.

Pentagonal prisms of the highest accuracy using optical contact tooling

The schedule shown in table 9.4 lists the operations that are necessary to achieve this final angular quality.

Operations 1 and 2: Issue of material and sawing to shape

This work is similar to that described under operations 1 and 2 of the production schedule for Porro prisms of the first type (table 9.1).

Operation 3: Grinding the datum faces parallel and polishing one of them

These operations are very similar to operation 3 of table 9.1, except that in this case a datum face is to be polished so that it can be contacted with the master bar. The polishing of the datum face must be to a very high standard so that it is possible to contact optically each prism to the master block.

Operations 4–6: Cementing into groups, copy milling and decementing

These operations have already been described for pentagonal prisms of medium angular accuracy.

Operation 7: Grinding, polishing and deblocking for surface I, using optical contacting methods

The process that is now to be described is the key to manufacturing significant quantities of high-precision prisms; it is a process that requires a great deal of careful attention from highly skilled optical craftsmen if it is to be successful, but once the process is working well it is capable of producing a steady flow of high-quality work.

The optical contacting bars that provide the datum surfaces for this process are made to the very highest standards, and it is the precision of the angles of these bars that is transferred to the manufactured prisms. The vertical flanks of the optical contacting bars (shown in figure 9.19), against which the prisms are contacted, should be vertical to within 2 second of arc.

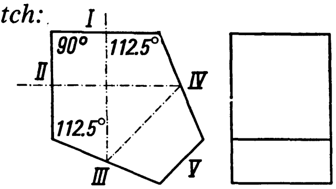
The tooling arrangement shown consists of a thick base plate of fine annealed glass, a number of contacting bars holding the prisms, a guard ring and two or more glass tubes to allow the parallelism to be checked during polishing.

The prisms are first contacted by their polished pentagonal reference faces to the tooling bars; the bars with their prisms are then contacted on to the base plate and finally the guard ring is contacted around the periphery of the block, the tubes

Table 9.4 Operation layout for manufacture of pentagonal prisms (angular tolerance ±5 seconds)

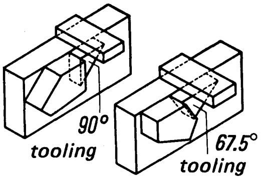
Type of job:
pentagonal prism
(±5″)

Sketch:



Angular tolerance ±5″

Drawing No.:



	Operation	*Process description*
1	Issue of material	See table 9.1, operation 1
2	Cut glass into prisms	See table 9.1, operation 2
3	Grind the reference sides parallel and polish one of them	Stick both sides of the prism blanks in turn on a flat tool and grind them parallel to the specified size. Polish one of the sides to a flatness of 0.1 interference fringes: this side is to be used for optical contacting
4	Cement the prisms to form groups and cement turning-nipples at the ends	Length of each group: Cementing of the groups is to be done with clean cement. The turning-nipples for profile milling (copying) are to be cemented with the help of a centration gauge
5	Profile milling	With the copying profile milling machine, the prisms are milled on all sides, keeping an allowance of 0.1 mm of extra material on each surface for smooth grinding
6	Decement and clean the prisms	Decement the prisms, taking care that the polished datum sides of the prisms are not damaged. Carefully clean the prisms
7	Optical contacting for the grinding and polishing of surface I	For the processing of surface I, the polished datum face is optically contacted to the side of the optical tooling bar and surface I is set along the top surface of the bar. The block is then fine ground to bring the worked surface parallel to the base plate. Next the block is polished and checked with an autocollimator to see that it is parallel to within 5″ and has a flatness of 0.1 of an interference fringe

Table 9.4 *Continued*

	Operation	*Process description*
7a	Unblock	Use hot air jet
8	Optical contacting for the processing of surface II	For the processing of surface II, the polished datum face of the prism is optically contacted on to the bars and in doing so surface I is set with a 90° angle block which enables it to be set at exactly 90° to the top surface of the bar. The top of the angle block is aligned with the top of the bar and adjusted by observation of the interference fringes on the top surface.
	Grind the block	See operation 7
	Polish the block	See operation 7
	Unblock	See operation 7
9	Optical contacting for the processing of surfaces III and IV	For the processing of surface III, the polished datum face is again optically contacted to the bar and, while doing the contacting, the surface II of the prisms is accurately adjusted to form a 67.5° angle with the top surface of the bar, with the help of a 67.5° angle block which is carefully and accurately set with respect to the top surface of the bar (see tooling diagram shown on top of this table). For processing of surface IV, the procedure to be followed is the same; however, in this case surface I is used for the purpose of alignment with the angle block
	Grind, polish and unblock	See operation 7
10	Chamfer the prism	See table 9.1, operation 21
11	Inspection of prisms	See table 9.1, operation 22
12	Rectification of prisms	See table 9.1, operation 23
13	Silvering of prisms	See table 9.3, operation 13

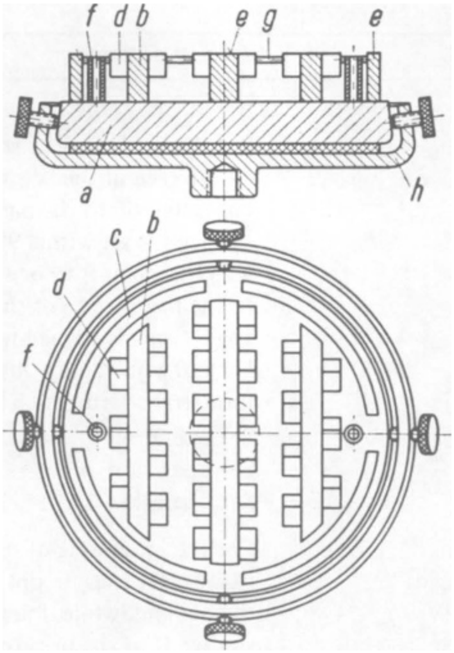


Figure 9.19 Optical contact tooling block. *a* Base plate, *b* datum bars, *c* guard ring, *d* prisms, *e* top surface of the datum bars, *f* glass tube, *g* layer of plasticine, *h* fixture with clamping screws and felt pad for mounting the block on the lever-arm machine

having been waxed into position when the bars were contacted to the base plate. The edges of the optical contacts are sealed with wax at each stage to avoid the ingress of water during processing.

The process of optically contacting the prisms and tooling bars consists of cleaning each pair of surfaces to be contacted with methylated spirit and possibly ether, and then freeing them of dust with a fine brush just before bringing the surfaces into contact. If the surfaces are sufficiently clean, interference colours are seen immediately and then, if the surfaces are also sufficiently flat, the application of pressure spreads the fringes out so that they cannot be seen and the surfaces grip each other as the pressure is increased.

As the tooling diagram in table 9.4 shows, the setting of prisms on the tooling bars at the correct attitude is of fundamental importance, but the tooling pieces shown there are only suitable for surfaces that have already been polished, and at this stage surface I has yet to be polished, so it is sufficient for surface I to be set with the surface of the tooling bar that is to be worked acting as a datum for a small flat setting piece that is held in position by hand as the prism is brought into optical contact. When surface I is polished it acts as a datum surface for setting the attitude of the prism during the optical contact blocking of the subsequent surfaces, as shown in the tooling diagram of table 9.4.

When the block is complete it is mounted on a standard lever-arm glassworking machine and smooth ground and polished using a slow speed and low pressure to avoid the prisms becoming detached from the tooling bars.

The parallelism between the datum base plate and the worked surface should be something like 3 seconds of arc, which requires a uniformity of wear over the block of 0.005 mm in a typical block of diameter 350 mm. The parallelism is checked using a high-precision autocollimator reading the simultaneous reflections from the worked surface and the base plate seen through the glass tubes.

When the polished quality and parallelism are satisfactory, the prisms and tooling bars are separated using a jet of hot air, which quickly produces local thermal deformation, so breaking the intimate contact between each pair of contacted faces.

Operation 8: Grinding, polishing and deblocking for surface II, using optical contacting methods

The instructions described under operation 7 apply to surface II also, although there is now the additional requirement to use surface I as a datum by setting the prisms on the tooling bars with the aid of the interferometric setting squares shown in table 9.4.

The angle between surfaces I and II should be controlled to within 5 seconds of arc if we are to achieve the final angular deviation requirement of 90° ±5 seconds of arc, and this is quite possible using careful observation of the interference fringes formed between face I and the setting squares. If surface I is 20 mm square, 5 seconds of arc corresponds to two fringes.

The technique used to set the prisms on the tooling bars consists of cleaning all the optical faces, placing the optical setting square on the narrow edge of the tooling bar so that it shows no interference fringes, and then sliding the pentagonal prism along the edge of the tooling bar until face I shows interference fringes with the setting square. Finally the alignment of face II with the narrow top edge of the tooling bar is checked and the prism is pressed into contact on the tooling bar.

Operation 9: Grinding, polishing and deblocking for surfaces III and IV using optical contacting methods

This operation is the same as that described under operations 7 and 8, although this time the setting square has an angle of 67.5° rather than 90°.

As in the case of Porro prisms of the first type where it is the 90° angle that must be accurate, but where it is the 45° angles that are used to control it, so too here in the case of the pentagonal prism, it is the angle between faces III and IV that must be accurate, but because of the geometry of the prism it is the other angles that are controlled to produce that accuracy.

If we consider the angular tolerances that are necessary on the angles that are being worked, we see that the prism replaces a pair of mirrors that would be in the same position as faces III and IV, and the first step in working out the tolerances is to consider just these two faces. If we consider the ray entering the mirror system, we see that any rotation of surfaces III or IV produces twice the angular deviation on the output ray, but because the mirror pair is insensitive to rotation as a pair, we can restrict our attention to the required accuracy of the angle between them. An error in the angle between faces III and IV of $d\theta$ produces a deviation of $2d\theta$ in the output ray angle, but because this deviation is actually taking place inside a glass prism of refractive index n, by the time the exit ray gets out into air it will have a deviation of $2nd\theta$.

In addition, if the input or output face is tilted by an angle $d\phi$, there is a further probable total deviation of the output ray by $\sqrt{2}\,(n-1)d\phi$ and together with the deviation produced by the error in the angle between faces III and IV we may expect a most probable worst case summation of

$$\text{probable worst total deviation} = \sqrt{(2nd\theta)^2 + \{\sqrt{2}(n-1)d\phi\}^2}$$

If we wish to restrict this error to, say, 10 seconds of arc, and we want the error contribution from the reflecting faces to be similar in magnitude to the error contributions from the 90° faces, we arrive at the conclusion that if $n \simeq 1.5$

$$d\theta = 2.3 \text{ seconds of arc}$$

and

$$d\phi = 9.9 \text{ seconds of arc}$$

where $d\theta$ is the tolerance on the angle between faces III and IV, and $d\phi$ is the tolerance on the angle between faces I and II.

However, because we are generating the 90° angle first and are then using faces I and II as datums for faces III and IV, we see that we will have to work the 90° angle to a higher precision than would otherwise be necessary. We may thus assume that the contribution to the final ray deviation from faces I and II will be effectively zero, and in this way we may double the allowance on the angle between faces III and IV to approximately 5 seconds of arc, and then work out the precision that is necessary in the 90° and 112.5° angles to achieve this.

Three angles contribute to the final accuracy of the angle between faces III and IV (1 x 90 and 2 x 112.5), and the error in each of these three contributes directly to the error in the angle that we are interested in, so we may set

$$\sqrt{3 \times e^2} = 5 \text{ seconds of arc}$$

where e is the tolerance on each of the three angles, and from this equation we see that $e \simeq 2.9$ seconds of arc.

Thus, if we can work the 90° and 112.5° angles to within 5 seconds of arc we may expect the overall ray deviation to be, at worst

$$\text{deviation} = 90^\circ \pm 17 \text{ seconds of arc}$$

where the 17 seconds comes from the scaling

$$17'' = 10'' \times \frac{5}{2.9}$$

and the 10 seconds of arc are the original choice of overall error.

Operations 10–13: Chamfering, inspecting, rectifying and silvering

These operations have already been described for Porro prisms of the first type and for pentagonal prisms of lower precision.

5 Roof edge prisms

In the Porro prism of the first type the 90° angle is of more importance than the 45° angles, which need only be worked to 5 minutes of accuracy.

In roof edge prisms the same situation exists but, because the aperture of the instrument is split by the roof edge, any departure of the roof angle from 90° results in double images, which cannot, of course, be tolerated. It is important to establish just what the implications of this situation are. If such a roof edge is L mm from an image plane, and the image forming pencils have a relative aperture of $f/5$, the image of a point source will have a characteristic diffraction point resolution radius given by

$$\text{resolution radius} = 1.22\lambda \times f\text{no} = 0.0033 \text{ mm in green light}$$

which is the celebrated Airy–Raleigh diffraction resolution formula and any error in the roof angle of, say, $d\theta$ produces an angular splitting in the plane perpendicular to the roof edge given by (see figure 9.20)

$$\text{angular splitting} = 4n\,d\theta$$

So the image splitting at the image plane will be

$$\text{image plane image splitting} = 4nL\,d\theta \cos i \text{ mm}$$

where i is the angle of incidence of the optical axis at the roof edge, and n is the refractive index of the prism. Thus, if

$$L = 20 \text{ mm}$$

$$i = 45^\circ$$

$$n = 1.56$$

and $\quad d\theta = 5$ seconds of arc $= 0.00024$ radians

then

$$\text{image plane image splitting} = 0.002 \text{ mm}$$

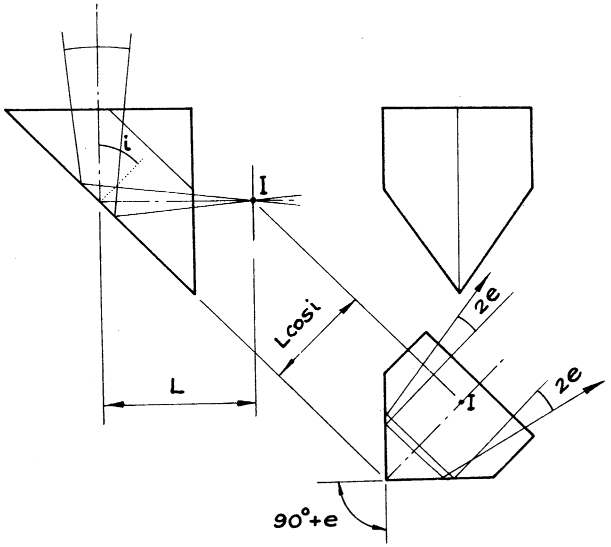


Figure 9.20 The geometry of roof prism errors

whereas the image plane point resolution radius in green light is approximately 0.003 mm, so this situation is just tolerable. Figure 9.20 illustrates the geometry of this calculation.

A further difficulty in the manufacture of roof edges occurs because to maximise the angular tolerance on the roof edge the prism should be as close to the image plane as possible, and any chips at the roof edge can therefore produce scattered light in the image plane. After polishing it can be beneficial to touch the sharp edge of the roof on a polisher to reduce the risk of chipping during instrument assembly.

The manufacture of roof edge prisms by hand methods

Table 9.5 shows the manufacturing plan for roof edge prisms by hand-grinding methods. This method is less economic than the method of processing which employs optical contact tooling, but for small numbers of prisms it may be necessary to use such methods, and it is included here to emphasise the difficulties involved in this process.

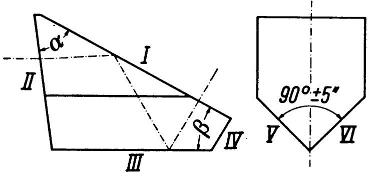
Operations 1–4: Issue of material, cut into prisms, grinding parallel and cementing into groups

These operations have already been described for the Porro prism of the first type (table 9.1).

Table 9.5 Working plan for the manufacture of roof edge prisms by hand-grinding method

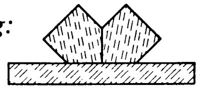
Type of job:
Roof edge prism
(hand grinding)

Sketch:



Drawing no.:

Tooling:



	Operation	*Process description*
1	Issue of material	See table 9.1, operation 1
2	Cut into prisms	See table 9.1, operation 2
3	Grind parallel	See table 9.1, operation 3
4	Cement into groups	See table 9.1, operation 4
5	Grind surface I	See table 9.1, operation 5
6	Grind surfaces II, III and IV	Grind by hand and check against angle gauge for light gap Surfaces I and II must form the angle $\alpha \pm 5'$ Surfaces I and III must form angle $\beta \pm 5'$ Surface IV must be ground to the size required All surfaces must be $90^\circ \pm 5'$ with respect to the datum side
7	Decement the groups	With the help of heat, separate the prisms from one another
8	Chamfer the prisms	Grind a protecting chamfer on all edges
9	Embed in plaster of Paris for the grinding of roof surfaces V and VI in turn. Grind and unblock	See table 9.2, operations 16 and 17. In this process, surface III and the reference sides serve as datums for blocking in V-blocks. Grind the roof surface to the specified size: The same operations are performed for grinding both surfaces V and VI. See table 9.1, operation 14
10	Grind chamfer	As indicated in the drawing
11	Hand correct the compound angles and the 90° angle; coarse polish one roof surface	The compound angles in the case of roof prisms are those angles that either of the roof surfaces make with a particular reference surface; these angles must be equal, so that the direction of the roof is correctly inclined.

Table 9.5 *Continued*

	Operation	*Process description*
		In this case we take surface I as the reference, and then the angle of surface V to surface I must be equal to the angle of surface VI to surface I; the angle of surface V to surface VI should also be 90°. Surface V is then coarse polished for the purpose of contacting the prisms in pairs
12	Polish surfaces I and II in plaster of Paris blocks	See table 9.1, operations 11–14
13	Make pairs of prisms by optical contacting. Embed in plaster of Paris, grind and polish surface VI, take out the prisms from the plaster of Paris and decontact the prism pairs	The polished roof surfaces of every pair of roof prisms are optically contacted, with the help of an accurately flat plate, so that the exposed roof surfaces become a single surface (see the tooling diagram). Rub and lay the prism pairs on a flat tool until they give the feeling of sucking contact. See table 9.1, operations 11–14
14	Inspect the 90° angle and correct it by polishing	The accuracy of the 90° angle is next checked for any error down to 5 seconds of arc by placing the prism in the ray path between a telescope and a pin hole or on a Twyman-Green interferometer and then correcting errors in excess of 5 seconds of arc by hand as necessary
15	Optically contact the prisms together into pairs, lay the prism pairs on flat tool, embed in plaster of Paris, grind, repolish surface V, unblock and decontact them	The prisms are grouped together into pairs and their finish polished surfaces VI are optically contacted; in doing so it must be also checked that when a flat test plate is applied on the exposed roof surfaces of the contacted pair, it should show continuous interference rings. The exposed roof surfaces of the prism pairs are rubbed to a sucking contact on a flat tool. See table 9.1, operations 11 to 14
16	Final inspection and rectification	See operation 14

Operations 5 and 6: Grinding surfaces I, II, III and IV

These operations are very similar to operations 5 and 6 in the manufacturing plan for Porro prisms of the first type (table 9.1), although the linear dimensions and angles are of course different.

Operations 7 and 8: Decementing the groups of prisms and chamfering

See operations 8 and 10 in table 9.1.

Operation 9: Blocking in plaster of Paris, grinding roof surfaces and deblocking

For the grinding of the roof surfaces one requires equipment that is similar to that described for operations 16–19 in the manufacturing plan for Porro prisms of the second type (table 9.2).

Operation 10: Grind chamfer

See operation 10 of table 9.1.

Operation 11: Grinding compound angles and the 90° angle, polishing surface V

The symmetry and position of the roof angle is now generated with reference to surface I.

The compound angle between the roof faces and surface I is not shown in the diagram in table 9.5, but it may be calculated in the fashion shown in figure 9.21, where the prism is shown resting on a surface plate by the ridge of its roof. The surface normal to face I is shown extended to the point N and if the prism is allowed to rotate about its ridge line the point N rotates around the surface of a cone to the point N′, when one of the roof faces is flat on the surface plate. The angle θ is the angle at which an autocollimator would have to be set to take a reflection from face I if the prism was lying on one of its roof faces, or the complement of the angle at which the blades of a protractor gauge would have to be set. For example, suppose $\beta = 30^\circ$, then θ will be $37.76124^\circ = 37^\circ 45' 40''$, and a protractor gauge would have to be set to $52.23876^\circ = 52^\circ 14' 20''$, if it was to lie simultaneously along face I and face V or VI.

If a sample finished prism is available it may not be necessary to calculate the compound angle, but merely to set the protractor to the sample prism faces, and then use that setting to achieve the compound angle.

When the roof faces have been formed it is then necessary to polish one of them so that the prisms may be paired and optically contacted for further processing. This polishing is best done by hand.

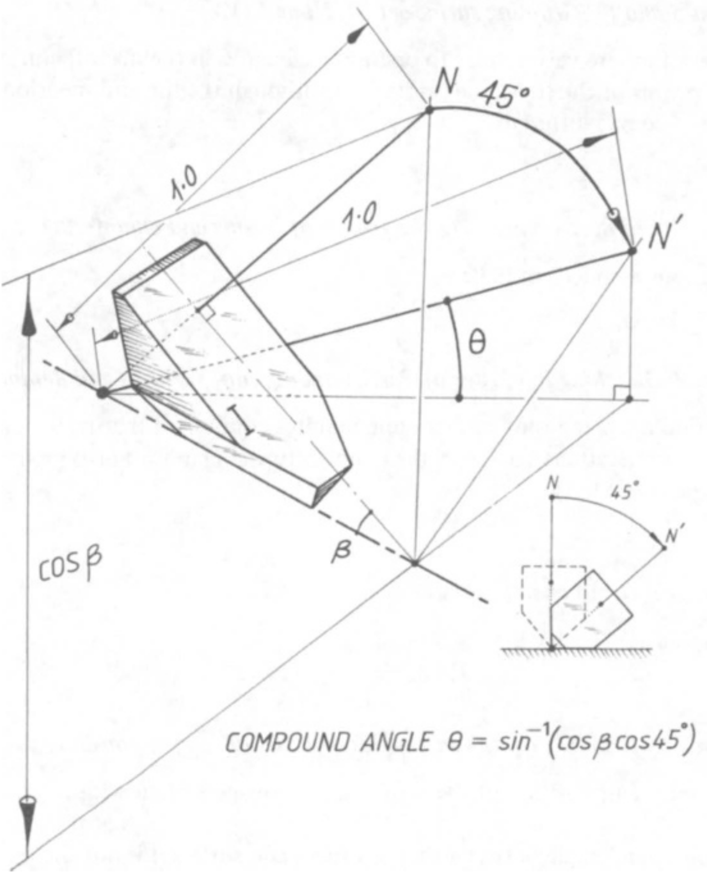


Figure 9.21 Calculation of compound angles

Operation 12: Blocking in plaster of Paris for the processing of surfaces I and II. Grinding, polishing, deblocking and applying protective lacquer

These processes are similar to operations 11–14 of the production scheme for Porro prisms of the first type described in table 9.1.

Operation 13: Blocking in plaster of Paris for the processing of surface VI. Grinding, polishing, deblocking and separating the optical contact

If the prisms are contacted together in pairs by their surfaces V it is possible to achieve a good flat surface for surfaces VI right up to the edge of the roof.

When the prism pairs are securely contacted and wax sealed they are then set on a flat tool and the plaster of Paris is cast around them, as has previously been described.

The plaster block is completed, and the rest of the processing proceeds in a fashion similar to operations 11–14 in table 9.1, although care is taken to minimise the wear at the fine grinding stage, to avoid any change in the angles.

Operation 14: Angular rectification by polishing

It is now necessary to work surface V to 90° with respect to surface VI. At this stage both surfaces V and VI are polished and the angular error between them may be measured on an interferometer or with a precision autocollimator. The measured error may then be used to correct the angle for each prism by hand work based on the experience of the craftsman. This work is similar to that described for Porro prisms of the first type.

Operation 15: Reblocking to repolish surface V

To achieve the required surface shape and cosmetic quality for surface V right up to the roof edge, it is usually necessary to work the prisms in pairs again as described for surface VI in operation 13.

Operation 16: Final correction and inspection

The final inspection is performed with a telescope viewing a pin hole through the prism, or by putting the prism roof in the test path of a Twyman-Green interferometer. Any angular or surface form correction must be done by hand polishing as described before.

The quantity production of roof prisms

From the description of operations 11 and 13–15 of table 9.5 it is clear that the hand correction of roof edges is an extremely expensive and complicated process, and, if any quantity of prisms is to be manufactured, a more economic method of working must be found.

The use of the mandrel fixtures described in the section on Porro prisms and pentagonal prisms, combined with the technique of optically contacting prisms to precision tooling bars, provides just the required improvements in the economy of the process.

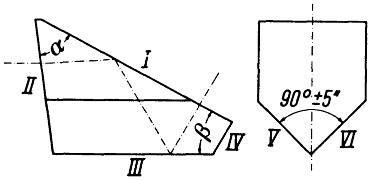
The manufacturing plan in table 9.6 describes the manufacture of roof prisms using these methods. Operations 1–4 are, again, similar to the same operations described for Porro prisms of the first type, and then the prism blanks are cemented to form sticks and surfaces I, II, III and IV are milled using a copying mill of the type used for pentagonal prisms.

Surfaces I and II are ground and polished first and then lacquered before the prisms are mounted in the fixture shown in figure 9.22. The fixture shown for the milling, grinding and polishing of surfaces V and VI works in an identical fashion to

Table 9.6 Working plan for manufacture of roof edge prisms in fixtures

Type of job:
Roof edge prisms
(processing in fixtures)

Sketch:



Drawing no.:

Tooling:

	Operation	*Process description*
1	Issue of material	See table 9.1, operation 1
2	Cut into prism blanks	See table 9.1, operation 2
3	Grind parallel	See table 9.1, operation 3
4	Cement the prism blanks into groups	See table 9.1, operation 4
5	Mill surfaces I, II, III and IV	See table 9.4, operation 5 (copy milling method used for pentagonal prisms)
6	Embed in plaster of Paris blocks, grind and polish surfaces I and II and then unblock	See table 9.1, operations 11–14
7	Decement the groups and clean	See table 9.1, operation 8
8	Grind chamfer	As indicated in the drawings
9	Clamp in fixtures for the processing of surfaces V and VI	(See manufacture of Porro prisms from mouldings.) For milling of roof surfaces, the prisms with their finish polished surfaces I and II are laid in bar-shaped fixtures and fixed with clamping plates. For the protection of the polished surfaces, tissue paper is laid on the datum faces of the fixture
	Mill	The roof surfaces are milled by the copying method
	Grind	The loaded mandrels are next put at appropriate positions on a flat tool to form the working surface of the prism block. The prisms are firmly clamped in position by the transverse pressing plates, so in this way the opposite face of the mandrel is resting against

Table 9.6 *Continued*

	Operation	*Process description*
		the accurate flat surface of the tool and this serves as an accurate datum for the alignment of the surfaces that are to be worked. The surfaces are ground only with fine emery and only so long as to ensure that the individual surfaces of the prisms are covered by this fine grinding
	Polish	See table 9.1, operation 13. Surface VI is only to be coarse polished
10	Optical contacting of roof surface V for the reworking of roof surface VI	For the purpose of achieving the necessary accuracy of the roof surfaces, surface V is optically contacted to the side of the bar of the optical tooling such that surface VI is coplanar with the top surface of the bar. This is done with the help of a flat plate placed on the top surface of the bar and surface VI. In doing so one must ensure that the interference fringes run continuously over both the surfaces
	Grind, polish and break the optical contact	See table 9.4, operation 7
11	Final inspection and rectification, if necessary	See table 9.5, operation 14

that described for Porro prisms of the first type. Surface V should be polished accurately flat for the purpose of optical contacting, but surface VI need only be coarse polished to enable the intermediate sample checking of the optical quality of the prisms.

The prisms are next removed from the mandrel fixture, cleaned and contacted to the precision tooling bars as shown in figure 9.23. This contacting is performed in the same way as was described for high precision pentagonal prisms, using the same tooling and processing methods.

The manufacture of optical contact tooling bars

For the rational and economic production of precision 90° angles for pentagonal and roof prisms, the tooling bars described above must be manufactured in some quantity and then recycled as they become worn during prism manufacture.

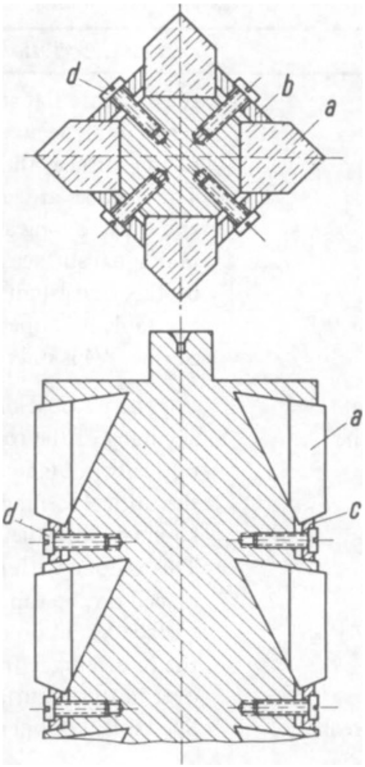


Figure 9.22 Clamping fixture for the initial processing of roof prisms. *a* Roof prisms, *b* side clamp, *c* end clamp, *d* clamp screw

The angular tolerances on the 90° corners of these bars should be approximately one-third of that required on the prisms, so if the prism angle tolerance is 5 seconds we require tooling bars with angular tolerances of 1.5–2 seconds of arc.

The first master pair of bars must be made in a particularly laborious fashion by checking each pair of angles, as shown in the tooling diagram of table 9.5, until all four 90° corners will mate with any of the four corners of the other bar.

These two master bars may now be used to reproduce the next generation of

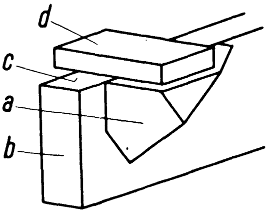


Figure 9.23 Optical contacting of roof prisms. *a* Roof prism, *b* precision optical contact bar, *c* top surface of optical contact bar, *d* flat test plate

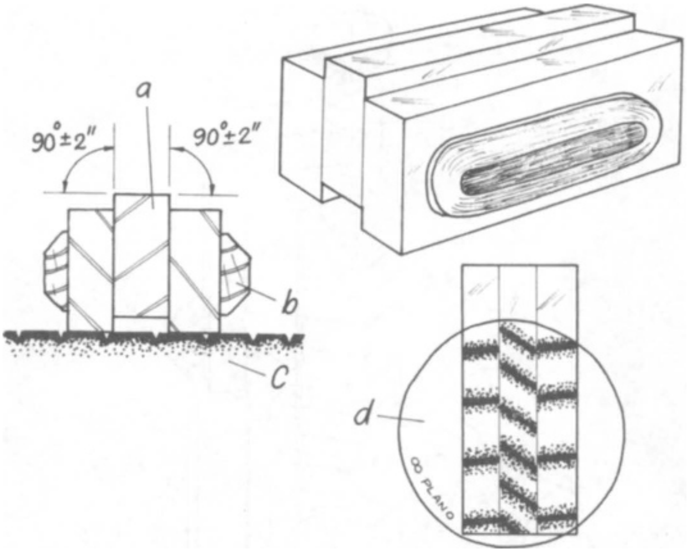


Figure 9.24 Reproducing master tooling bars. *a* Master bar, *b* wooden handle, *c* polisher, *d* test plate

bars in the fashion shown in figure 9.24. These groups of three bars are worked by hand until the worked surfaces of the outer bars are parallel to the narrow face of the master bar.

Refurbishment of bars that have deteriorated during use can, of course, be speeded up by first working them in contact with other, better, production bars before finishing them off in the fashion of figure 9.24. At this stage it may also be possible to make up a block, with the master bars contacted to the base datum and the edges of the bars that are to be refurbished standing proud of the master bars.

To prevent the transfer of heat from the hands during the final hand-polishing process, wooden handles should be cemented to the outside of the groups of three bars using a cold-setting cement.

The smoothing and polishing water should be at room temperature, and the temperature of the room should not fluctuate by more than 2°C. The greatest danger of temperature fluctuation comes at night when the workshop may cool down as a result of the heating or air conditioning being shut off, and it is vital that this is avoided because it may take most of the working day to restabilise the temperatures of the pieces of glass, the polishing fluids and the polishers.

Mass production of prisms

When prisms are required to be mass produced, additional tooling must be provided and the glass will normally be supplied in the form of mouldings.

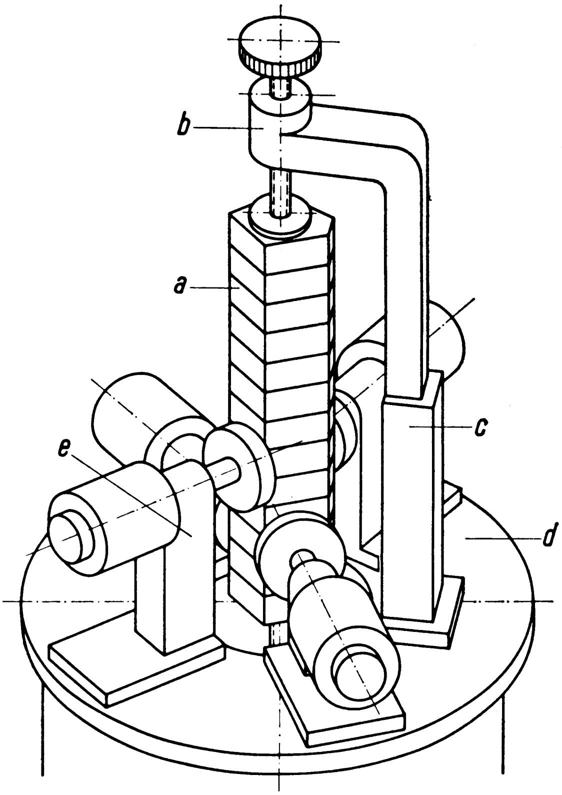


Figure 9.25 Schematic view of a multiple spindle milling machine for pentagonal prisms. *a* Stack of prisms, *b* clamp, *c* linear slide for traversing prism stack, *d* machine table which may be magnetic, *e* milling cutter spindle head which may be adjusted to a master template prism

At the roughing stage, a machine of the type shown in figure 9.25 is required. This machine is provided with a milling head for each face of the prism, so allowing a single pass of the stick of prisms, rather than a pass for each face and the requirement for indexing between each pass.

The schedule of operations is now as follows:

Operation 1: Mill reference faces parallel.
Operation 2: Stick prisms into groups.
Operation 3: Mill prism form.
Operation 4: Cement prisms to metal jigs.
Operation 5: Mount the metal jigs holding the prisms on a magnetic face plate and grind and polish.

We shall take as an example a typical pentagonal prism to clarify the description of the processes. The milling of the parallel reference faces is performed on equipment which is similar to that used for Porro prisms of the first type, that is, similar to the arrangement shown in figure 9.1.

The milling of the pentagonal form shown in figure 9.25 may be performed with the prisms clamped without cementing if the reference faces are large enough, otherwise it is necessary to cement them into sticks, so that they may resist the pressure of the milling cutters. The milling cutters are initially set by reference to a master prism.

After milling, the prisms are cemented to their precision jig pieces as shown in figure 9.26, in the same fashion as Porro prisms of the first type were for mass production; the prisms (on their metal adaptors) are then held on a magnetic surface plate for further processing on a standard lever-arm glassworking machine.

For a pentagonal prism it is necessary to have two types of jig pieces to enable the polishing of both types of angle that this prism has.

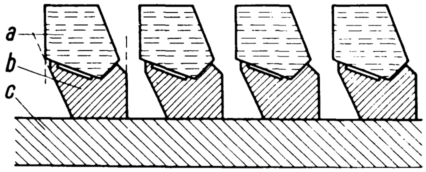


Figure 9.26 Precision jig pieces to hold prism stacks on a magnetic chuck table. *a* 'Stick' of prisms, *b* jig pieces, *c* magnetic chuck table to be fitted on the work spindle of a standard lever-arm optical processing machine

Mass production methods in optical production engineering

Where the quantity of optical components permits, it is possible to achieve considerable increases in manufacturing speed by the reorganisation of the glass-processing workshops and by the introduction of high-speed processing methods.

In particular, considerable gains can be made by grouping process stages together, so avoiding the storage and handling of glass between processes. Thus, a rationalised arrangement would consist of the following processes following on directly from each other: blocking, milling, grinding, polishing, deblocking, cleaning, edging and testing. In this arrangement there can be a continuous flow of a particular component with a feedback loop through a parallel production line to process the second side if it is a lens. When an adequate stock of this component has been completed the machines can be reset for the next component and that can be run through in the same may until there is a matching stock of that component, or alternatively a separate production line can be set up to process each component.

Once the optical components are finished-edged they need to be handled in a suitable environment for vacuum coating, cementing, assembly and testing, and in a mass production situation these processes will be carefully segregated from the glassworking areas.

High-speed processing methods also contribute to increased manufacturing speed.

The notable examples of these methods that have given most in this direction are diamond smoothing and polyurethane polishing. Not only do diamond smoothing and polyurethane polishing reduce process times but, more importantly, they are more stable during production and therefore last longer between replacements and are less demanding on the skill of the operator. Loose abrasive fine grinding is a difficult process to control and is particularly responsible for variations in the thickness of finished lens components; diamond smoothing is fast and consistent, and is capable of producing finer surface finishes with much more consistent and smaller stock removals. Polyurethane polishing exhibits similar operational characteristics to diamond smoothing, and in addition it offers great stability of curvature, unlike pitch, so that the glass worker spends far less time controlling curvature, which is one of the main time wasters with pitch polishing.

Although these high-speed processing methods work very well when they are properly adjusted, the initial setting up requires a high level of technical skill, because both diamond smoothing and polyurethane polishing can only work when they are fed with surfaces of precisely the right curvature. Both processes must still work with ‘edge bite’, but whereas with conventional processing a surface can be retrieved from an unacceptable state of curvature by an adjustment of the machine stroke or a quick scrape of the polisher, in the case of diamond smoothing and polyurethane polishing such adjustments are either ineffective or unacceptable.

The technology of these two high-speed polishing methods is straightforward. Diamond smoothing tools are made up with copper alloy pellets impregnated with diamond grit. These pellets are of a standard thickness and they may be cemented to the surface of a carefully prepared cast iron shell runner so that the active surface of each pellet lies close to a spherical surface of the chosen radius, a slightly shorter radius than finally required for concave tools and slightly longer for convex tools. The tool may then be worn-in to the correct radius by working the pellets against a smooth grinding tool with conventional loose abrasives which erode the copper alloy base.

Polyurethane polishers are similarly straightforward. The polyurethane is supplied in sheets of a standard thickness of approximately 1 mm, the polisher petal pattern is cut or stamped from the sheet and cemented on to the surface of a carefully prepared spherical tool. The petals of the polisher configuration are necessary to avoid the crinkles that would result from trying to cement a simple circular polisher on to a spherical surface. After the polyurethane film is pressed into contact with its runner and the cement has set it may be worked to the correct smoothness and radius with normal glassworking abrasives on a cast iron smooth grinding tool.

Other advances in processing that contribute to increased efficiency are induction heating for blocking and deblocking, plastic collet holders for lens components while they are being polished (to avoid cementing of components to their tooling), automatic vacuum plant cycling for antireflection coating and continuously dressed laps for working flat surfaces.

10

Process Materials and Process Control

Just as the metal worker must know about the properties of the tool steels that he uses for cutting, so too must the glass worker know about the action of the abrasives and polishing compounds that he uses. Similarly, the metal worker has to work with several different metals and alloys, each with their own hardness and cutting properties, whereas the glassworker has many different optical glasses and crystals to consider.

Because of the wide variety of abrasives, glasses and polishing techniques, glassworking has the reputation of being an art rather than a science. Each combination of glass and abrasive works in a different way, each polisher works differently, especially if the temperature varies, and the staining characteristics of glasses vary unless the water supply is standardised. All these factors and more contribute to the 'artistic' reputation of glassworking and traditionally the skilled glassworker has had to learn to read every possible clue as to the condition of his materials and the rate at which any particular process is proceeding.

With the more widespread use of specialised glasses with poor processing characteristics and the requirement for tighter tolerances on lens thicknesses it has become even more necessary to apply scientific methods to the development of each processing situation, so that the precise rate of stock removal is known, the appropriate grades of pitch and wax are available for each job, the temperature of the workshop is constant and the chemical composition and acidity or alkalinity of the water supply are controlled to within tight limits.

The important step that must be taken to achieve consistent results is the standardisation of materials, temperatures, chemical compositions and process details. In a glass workshop with a wide variety of work and range of glassworking experience, a high level of discipline is necessary to avoid individual workers introducing special abrasives and polishing potions.

This upgrading of the scientific basis on which glassworking is founded is of fundamental importance to the profitability and quality of the work that is produced. It also has an important bearing on the status and pride of the craftsmen, and on the quality of the training that apprentices can be given. At worst, glassworking is a disorderly, erratic, costly and dirty business, although it can be highly productive, reliable and clean, with the associated status and rewards for the craftsmen and technicians involved.

Loose abrasive smoothing

There is a wide variety of loose abrasives available for glassworking and it is important to standardise on one matched range of powders that produces the necessary results on the range of glasses that are processed by any one workshop.

The relationship between surface smoothness or roughness and the grit size of the abrasive is dependent on the hardness of the glass that is being worked, but as an example, figure 10.1 shows the effect of different grit sizes on the surface roughness of a sample of borosilicate glass (Bk7 517642).

The relationship plotted in figure 10.1 is determined using the pneumatic gauge shown in figure 10.2. The gauge shown detects the different surface roughnesses, but to determine a quantitative value for the roughness depth it is necessary to calibrate the results by measuring the thickness of test pieces before polishing and when the polishing is just completed.

The pneumatic device shown in figure 10.2 may be used as a production tool rather than depending on the eye of the craftsman looking at the surface through a magnifier, although visual inspection is still necessary to check for scratches and uniformity of texture. Owing to the random nature of the abrasive action and the fracture properties of glass surfaces this pneumatic gauge is capable of surprisingly

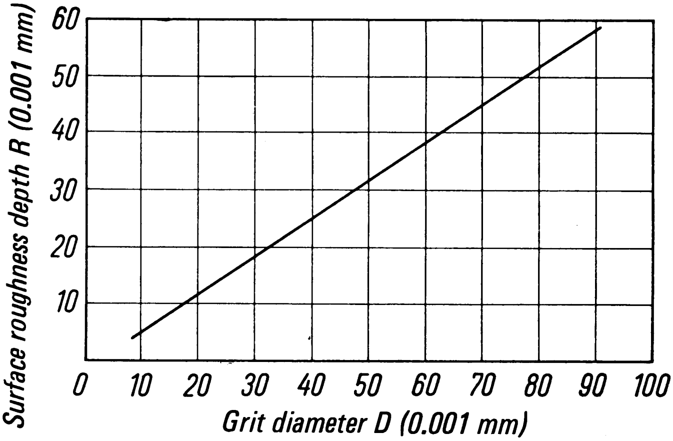


Figure 10.1 Surface roughness depth on Bk7 glass for a range of abrasive grit diameters

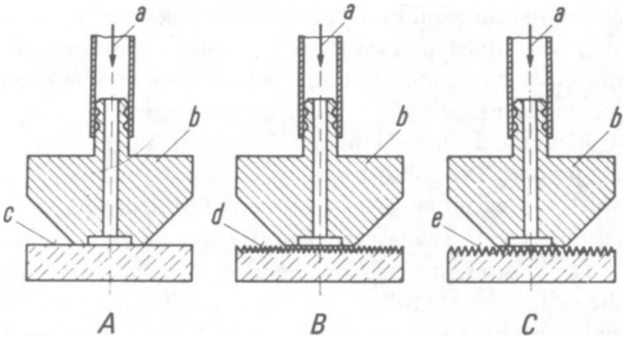


Figure 10.2 Evaluation of surface roughness using a pneumatic probe: (A) air stream blocked, (B) slight leakage, (C) gross leakage. *a* Air stream, *b* measuring nozzle, *c* polished surface, *d* fine ground surface, *e* rough ground surface

reliable results, and it can therefore lay a sound foundation for consistent polishing times, so improving the rhythm of the work.

The loose abrasives used by optical workshops range in grit size from 0.003 mm to 0.175 mm in diameter, and this range is usually split into ten steps, although any one workshop will usually standardise on only a few of these. Each grade of abrasive should have a very narrow diameter spectrum to ensure that the surfaces produced have a uniform texture. The relative efficiencies of these different sized grits are shown in figure 10.3, where it is assumed that the abrasive is fed constantly in the form of a slurry rather than a single charge of grit being 'worked out'. The individual grit diameters listed in figure 10.3 each represents the range within which a particular grit will lie, whereas any specific abrasive should have a narrower diameter spectrum than those values suggest. The lines on the graph of figure 10.3 show how the thickness of a sample of Bk7 glass 100 mm in diameter changes with time as each grit is used.

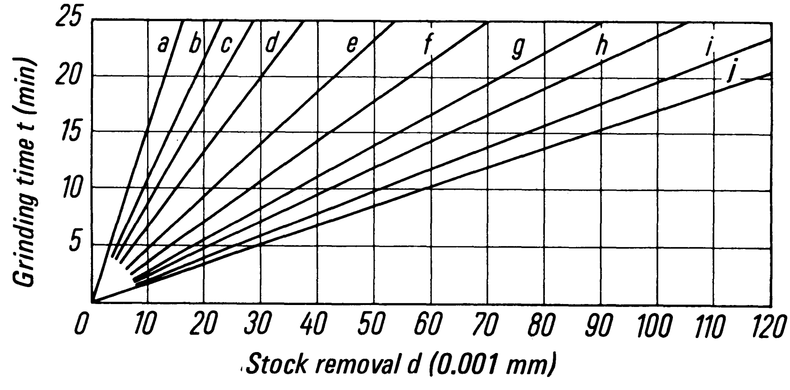


Figure 10.3 Grinding efficiency of different commercially available grit sizes: sample diameter = 100 mm, glass type = Bk7. Curve (a), grit size 5–7 microns; (b) 8–10; (c) 11–15; (d) 16–20; (e) 21–30; (f) 31–42; (g) 43–60; (h) 61–86; (i) 87–123; (j) 124–175

The polishing craftsman requires the finest possible scratch-free surface so that the polishing may be completed in the shortest possible time, and it is interesting to study the strategy that can be applied to smooth grinding to minimise the time and the final surface roughness.

Figure 10.4 shows the downward progress of surface roughness during the smooth grinding process. The polisher requires a surface roughness of approximately 0.002 mm (2 microns) magnitude and curves *a* and *f* of figure 10.4 show a slow and a fast sequence respectively. The fast sequence is based on 10 minutes of work with each of seven abrasives, and the slow sequence is based on 15 minutes of work with each of the same seven abrasives, each sequence ultimately reaching the 0.002 mm level of surface roughness. In practice, if the workshop conditions or the abrasive quality is not correct the sequence may be more like curve *b* in figure 10.4

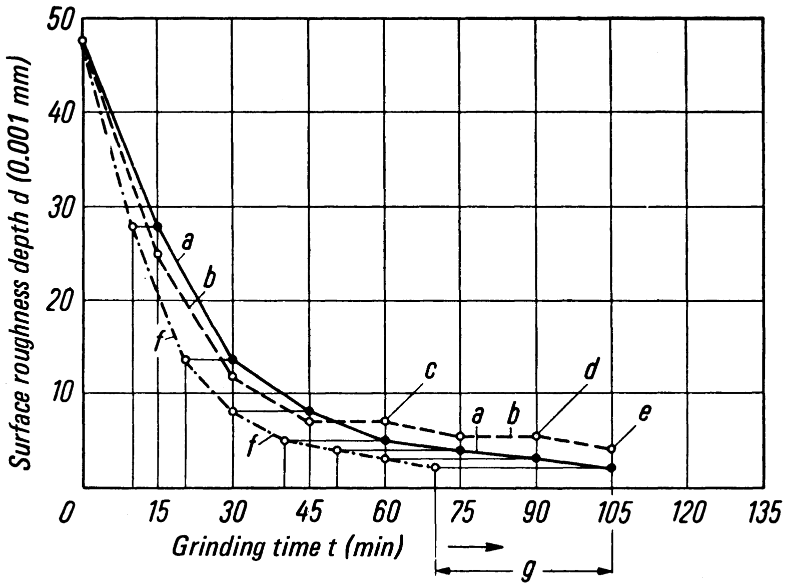


Figure 10.4 Measured roughness during the grinding process. *a* Normal sequence of steps, *b* poorly matched sequence of abrasive steps, *c* and *d* the result of a stage of grinding that has not improved the surface texture, *e* unsuccessful conclusion of curve *b*, *f* well-matched sequence of abrasives steps, *g* saving in grinding time

where, as the finer surface textures are approached, each stage of grinding does not necessarily produce the planned reduction in surface roughness, and the final 0.002 mm texture is never reached.

The sequence shown in figure 10.4 is unnecessarily lengthy and, with modern abrasives, two or three steps with carefully chosen grit sizes are all that are necessary to reach the required state of surface smoothness.

Diamond smoothing

A typical diamond smoothing pellet will consist of an 8 mm diameter copper alloy disc, 2.5 mm thick and impregnated with 25–45 per cent of diamond grit. This may have a grit size in the range 0.006–0.012 mm for the first stage of grinding (immediately after curve generation) or a grit size of 0.002–0.006 mm for the final stage of smooth grinding in the case of spherical work.

These pellets are cemented on to their base tool with a heat-cured (1 hour at 100°C) cement consisting of an epoxy resin mixed with its specified hardener and 20 per cent aluminium powder and 5 per cent colloidal silica. In the case of spherical surfaces 33 per cent of the tool area should be occupied by pellets, and in the case of flat surfaces 20 per cent of the tool area should be occupied. So in the case of spherical surfaces, 8 mm pellets should be spaced on a triangular mesh pattern approximately 13 mm apart and in the case of tools for flat surfaces 8 mm pellets should similarly be spaced 17 mm apart.

For spherical surfaces two stages of grinding are necessary and the preparatory curve generation should produce surfaces that can in the usual way be brought to edge contact the test plate to the extent of eight interference fringes (0.002 mm difference in surface sag) for the first stage, and then taken to four interference fringes by the second stage. The cycle times for these two stages may typically be 30 seconds each, the first stage removing 0.050 mm of material and the second stage removing 0.012 mm. The cutting fluid used is similar to that used in metalworking: a milky colloidal suspension of oil in water which must be filtered to remove any particles larger than 0.008 mm for the first stage or 0.004 mm for the second stage, corresponding to a cotton element filter in the first case and a centrifugal filter in the second case.

Measurement and control of surface finish

An important practical indication of the state of readiness of a surface for polishing is the angle of incidence at which the surface begins to reflect specularly, that is, like a mirror. If the filament of a lamp is viewed by reflection from the smooth-ground surface no image will be seen unless the angle of incidence approaches 90°, and it is the extent to which one has to approach the 90° angle of incidence that indicates the smoothness of the surface. The reflection that is seen is reddish, owing to the preferential scattering of blue light.

An instrument based on the above experimental situation is shown in figure 10.5, where a photoelectric detector is arranged to accept the radiation from a symmetrically positioned lamp so that the reading from the photoelectric cell is an indication of the reflectivity of the surface at that particular angle of incidence.

As long as the surfaces are free of grease, this instrument is capable of very sensitive comparisons between surface textures and this allows the workshop technologist to identify variations in grit size or process operations.

The difference in roughness between the hardest crown glass and the softest flint glass worked with the same abrasive in the same way is approximately equivalent to one of the steps on the curves shown in figure 10.4, and the same level of surface smoothness may be achieved on flint glass as on crown if the abrasive is worked out until the grinding tool becomes black.

Polishing rouge

Several different polishing powders are available, but probably the most frequently encountered in Cerium oxide. Any particular glass workshop must try different polishing powders if it finds that cerium oxide is not suitable for its work, and then standardise on the alternative, after deciding on the procedure for cleaning and filtering the powder received from the supplier.

Diamond milling tools

Table 10.1 lists the diamond content of several grades of milling tool together with the corresponding grit sizes in terms of DIN standard 848.

Not only are the characteristics listed in table 10.1 important but also the bonding strength of the base material, because the speed of cutting depends to some extent on the ease with which the grains of diamond can work loose from their bonding.

Because of the inherently high cost of diamond, it is important to purchase the correct tool material so that diamond shall not be wasted through inappropriate usage.

The diamond tool suppliers have their own notation for describing each lap material and it is important to clarify with the supplier the exact specification of the tool to be supplied, otherwise all sorts of problems can arise when the tools are used. In particular, it is possible to calculate the total number of carats of diamond that are being purchased in each tool and then calculate the cost of that in terms of the current standard price of industrial diamond, so checking whether a particular tool is good value or not.

Cooling oil for milling

In the process of milling it is necessary to employ a suitable cutting fluid to carry away the glass powder and the heat generated by the cutting action.

The viscosity of this oil should be low enough to allow the glass powder to settle out of suspension in the settling tank of the machine, but it should also not deposit its load of glass powder on the bed of the machine or anywhere else where it is not required.

Table 10.1 Practical examples of the diamond content in optical milling tools

Item	*Grit size according to DIN 848*	*Diamond concentration carats/cm^3*	*Diamond content (Percentage of volume)*
Slitting blades 400 mm diameter	D 250	1	5.7
Slitting blades 150 mm diameter	D 250	2	11.4
Edging tool for centring	D 50	4	22.8
Cup-shaped milling tools for fine milling on block holders	D 70	4	22.8
Initial rough milling with barrel tools	D 150	4	22.8
Rough milling on rounding machine (cylindrical milling)	D 250	4	22.8
Milling tools for block holders (finest)	D 7	5	28.5
Milling tools for block holders (fine)	D 15	5	28.5
Milling tools for block holders (medium)	D 30	5	28.5
Profile and groove-milling tools	D 100	5	28.5
Cup-shaped milling tools for block holders up to 30 mm diameter	D 100	5	28.5
Chamfer milling on centring machine	D 30	6	34.2
Fine milling with barrel-type tool	D 100	6	34.2
Cup-shaped milling tools for block holders above 30 mm diameter	D 100	6	34.2
Milling tools for prism surfaces	D 100	6	34.2

The ignition point of the oil should also be above 150°C to minimise the risk of fire, and it should be resistant to the formation of spray which may be inhaled by the operators.

The oil is recycled once it has deposited its load of powdered glass in the settling tank, and eventually its cooling and carrying properties become degraded so that it is necessary to supplement the fluid with restorative agents to maintain the necessary efficiency.

Polishing pitch

Polishing pitch is a complex mixture of organic compounds, and the recipes for it have evolved over many centuries in the hands of practical glassworkers who, when fully skilled, know intuitively exactly what they require from a polishing pitch.

The most important property of polishing pitch is its variation of viscosity with temperature. At room temperature the pitch should be brittle but, at the operating temperature reached as a result of frictional contact with glass in the presence of polishing rouge, it should be able to adapt itself to the form of the optical surface without flowing out of control. Any further increase in temperature should allow the pitch to flow to any new form dictated by the tactics of the polishing procedure, and then to be 'frozen' at the required form by the application of cool rouge and water.

While the polishing craftsman is working and adjusting the action of his polishing machine, not only is he distributing the wear over the optical surface but also steering the temperature of the polisher to the appropriate value so that it bites in just the required fashion.

Although pitches of different viscosities are required for different work under different conditions, it is vital that the viscosity of any one pitch may be compared with some objective scale of viscosity. For this purpose the glass workshop should be provided with a pitch hardness tester or viscometer such as is shown in figure 10.6 so that each batch of pitch made conforms to some chosen standard of viscosity.

The practical recipes for pitch vary considerably, but the following is a recipe

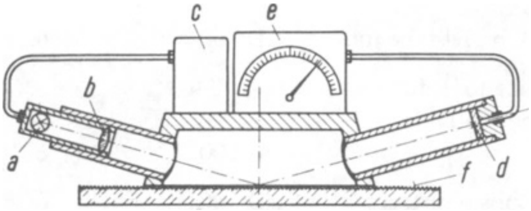


Figure 10.5 Gloss meter for smooth ground surfaces. *a* Lamp, *b* lens forming image of lamp on photocell, *c* power source (battery), *d* photoelectric cell, *e* voltmeter calibrated in surface roughness, *f* surface under test

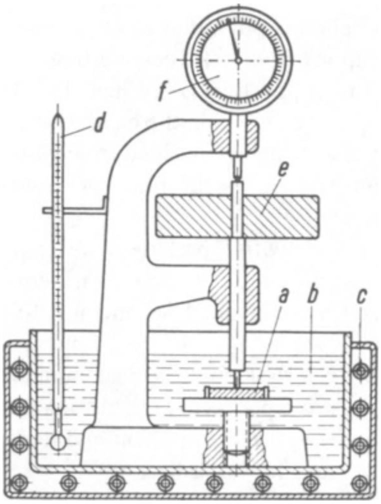


Figure 10.6 Pitch hardness tester. *a* Pitch under test, *b* water bath, *c* heating system, *d* thermometer, *e* weight, *f* micrometer dial indicator

that has been found to work well up to fairly high polishing pressures:

1 kg Swedish pine pitch
0.25 kg coal tar pitch
30 g resin
1 kg rouge
120 g hard-wood flour

The two pitches are heated together until the required hardness is reached and then the resin is added and the mixture stirred thoroughly before the wood flour is added and the mixture stirred again vigorously. Finally the mixture is strained through wet muslin cloth and tested for hardness as follows:

medium hard	0.020–0.030 mm per minute
medium	0.030–0.040 mm per minute
soft	0.050 mm per minute

where the temperature is 21°C, the point of the probe has a 20° cone angle and the loading is 200 g.

Cements and waxes

Several different cements and waxes are required for the range of tasks encountered in the glass workshop. In particular we may mention pelleting pitch, edging cement and the wax cement that is used to attach components to hard tooling.

The characteristics of pelleting pitch that must be achieved are associated with the need to hold lens components so that they are free of strain during processing but easily removable when the polishing is finished. The deblocking may be done by chilling in a refrigerator, or by striking the back of the block and so shocking the components off. In each case it may be decided to use a pitch whose properties have been modified to a different extent by the addition of beeswax and then heating to produce the required viscosity.

Edging cement may be made with 7 parts resin and 1 part beeswax. This mixture is simmered for 5 hours and then strained through muslin on to a warm metal plate that has been dusted with French chalk. The cement is formed into sticks and allowed to cool.

A general-purpose cement for attaching optical components to hard tooling may be made with 4 parts rosin and 1 part beeswax, but if a particularly thin wax is required to creep between an optical component and its seating without changing its angular position, ordinary paraffin wax is best.

PART II: OPTICAL CALCULATIONS, SPECIFICATIONS AND INTERFEROMETRIC TESTING

11

Optical Calculations

The professional optical technician is often required to determine the focal length of lenses, angular relationships in prisms, the effects of errors and tolerances and also perform a whole range of other miscellaneous calculations during the course of his duties. A search of the available manuals and textbooks reveals a shortage of suitable guidance: either the books are textbooks for physics undergraduates which deal with geometrical optics in a very limited fashion because it is no longer a fashionable topic, or they are advanced mathematical texts for postgraduate students of optical design. In neither case are the needs of the engineer catered for.

In the past, a further serious barrier for novices who wanted to get involved with optical calculations was the sheer labour of doing the mathematics using logarithmic and trigonometric tables. This barrier has been completely swept aside by the microelectronic revolution and everyone can own or have access to sophisticated calculators or microcomputers which can turn numerical drudgery into fun. The great advantage of calculators or computers for the novice is that they can be used to perform numerical experiments. Whereas previously the theory of a calculation had to be carefully refined before the laborious calculation stage was embarked on, we can now be somewhat wasteful of calculation effort and relax our obsession with the methods of calculation. For example, in chapter 14 we shall describe raytracing through an achromatic doublet to calculate aberrations; for simplicity and clarity only one set of raytracing equations is used, but this would have been unthinkable before the days of electronic calculation, when it would have been necessary to use paraxial raytracing and a separate special finite-ray raytrace to calculate chromatic aberration, in addition to the equations we shall use for that calculation.

Even with electronic calculators and computers there are many traps for the unwary, and mastery of the equations takes time and effort, but whereas before, books on optical design had to emphasise numerical checking and rigid discipline in paperwork, much of this is now looked after by the calculator or computer and the only general advice that is necessary is *have a go!*

All of what follows has been carefully selected as being of important practical value for the optical engineer.

Focal length, magnification and lens position

Usually the first time the need for optical calculation rears its head is in the context of focal length: 'What focal length of lens do I need to produce an image of such and such a magnification?' 'What is the focal length of the lens whose prescription I have here?'

By 'focal length' is almost always meant *effective* focal length, which is defined as the distance from the focal point to the position of a perfectly thin lens of the same focal length, as shown in figure 11.1. The position of the perfectly thin equivalent lens is different, depending on whether the light is travelling from left to right or right to left, but the effective focal length is exactly the same in both cases.

The positions of the simple equivalent thin lenses are shown at P and P′ in figure 11.1; these are known as the principal or nodal points (strictly speaking there is a theoretical difference between principal and nodal points but this

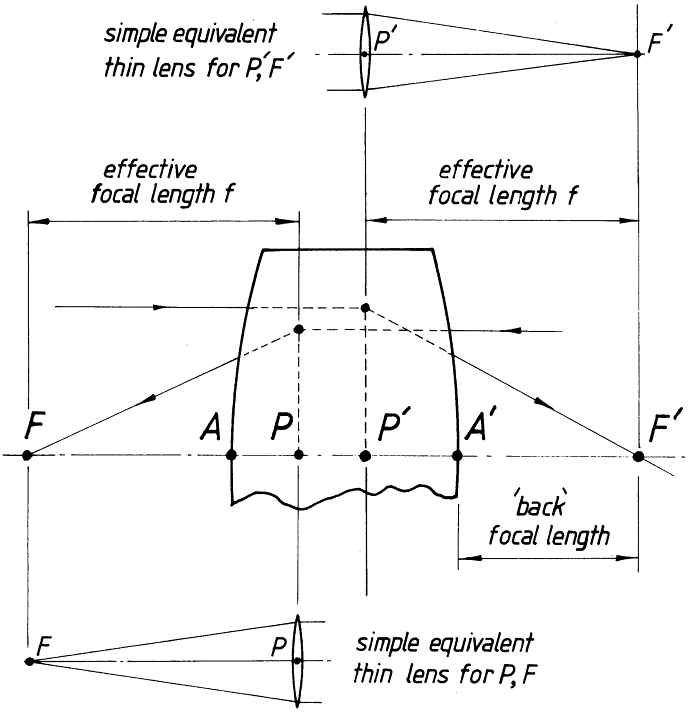

simple equivalent
thin lens for P′, F′
P′
F′
effective
focal length f
effective
focal length f
F
A
P
P′
A′
F′
'back'
focal length
F
P
simple equivalent
thin lens for P, F

Figure 11.1 Location of focal points and principal (or nodal) points

difference is almost always irrelevant). The principal points constitute the 'position' of the lens and they are datum points for many calculations. Unfortunately they are not mechanical points that can be measured to on an optical bench and probably because of this they are unpopular with most people except optical designers!

The thick lens shown in figure 11.1 may be simple, as depicted, or may consist of several components, but the principal points exist in both cases and their positions are determined experimentally or calculated theoretically in exactly the same way in each case.

We think of lenses forming images as either deviating rays, as shown in figure 11.1, or as distorting wavefronts, as shown in figure 11.2. If we plot a graph of wavefront curvature against longitudinal position (see figure 11.2) we see that, for an axial object point at the left-hand infinity, the wavefronts incident on the lens are flat; that is, their radius is infinite or their curvature is zero (curvature is the reciprocal of radius). The action of the lens is to impress a curvature of $1/f$ on to the wavefronts, which then proceed towards the focal point, increasing their curvature as they go, until, at the focal point their curvature is infinite (that is, they have zero radius).

The concept of the lens impressing a wavefront curvature of $1/f$ may now be applied to the derivation of the formula

$$\frac{1}{l'} = \frac{1}{l} + \frac{1}{f} \tag{11.1}$$

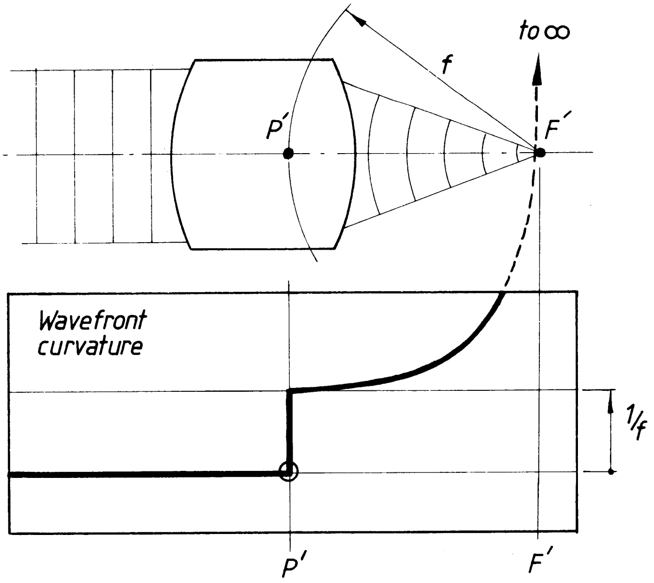


Figure 11.2 Wavefront curvature increment introduced by a lens of focal length f

which relates the object distance, image distance and focal length, as shown in figure 11.3. If the centre of curvature of a wavefront is to the left of the wavefront, we give its curvature a negative sign (and the distance OP = l is negative as well). Conversely, when a wavefront is focused on an object or image point to the right, we ascribe a positive sign to its curvature and the corresponding length. Examination of the graph of wavefront curvature shown in figure 11.3 allows us to write the above object and image distance equation straight down or, with a simple rearrangement, in a slightly different form

$$l' = \frac{1}{\dfrac{1}{l} + \dfrac{1}{f}} \tag{11.2}$$

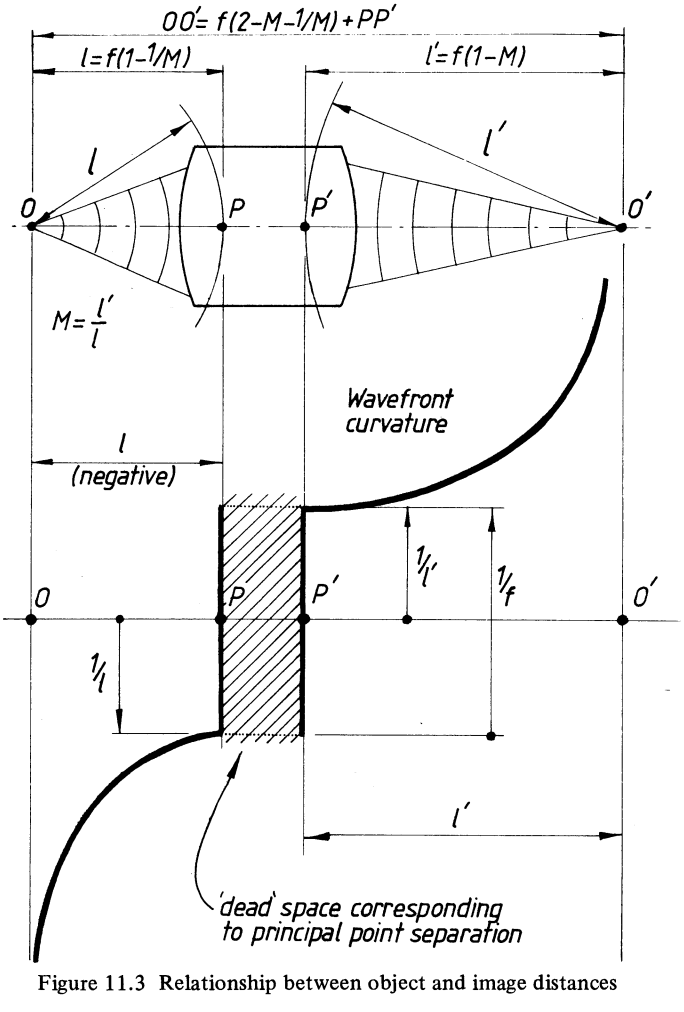

OO′= f(2-M-1/M)+PP′
l=f(1-1/M)
l′=f(1-M)
l
l′
O
P
P′
O′
M=l′/l
Wavefront curvature
l (negative)
1/l′
1/f
O
P
P′
O′
1/l
l′
'dead' space corresponding to principal point separation

Figure 11.3 Relationship between object and image distances

We can immediately see the practical value of this formula: if, for example, a lens with a focal length of 50 mm is used to form an image of an object placed 1000 mm in front of it (as in a typical 35 mm camera) the image distance will be

$$l' = \frac{1}{\dfrac{1}{(-1000)} + \dfrac{1}{50}} = 52.63 \text{ mm}$$

That is, the lens will have to be moved 2.63 mm from its infinity focusing position and, if this should be accomplished by turning the lens approximately half a turn on a focusing thread, a suitable lead for the focusing thread would be something like 5 mm, leading to an angular focusing rotation of

$$360^\circ \times \frac{2.63}{5.00} = 189.4^\circ$$

The magnification of the image is given by

$$M = \frac{l'}{l} \qquad (11.3)$$

So, in our example

$$M = \frac{52.63}{-1000} = -0.0526$$

That is, for our 50 mm lens focused on an object at 1000 mm from its front nodal point, all linear dimensions are reduced by this magnification factor. Note that this factor is negative, which may be thought of as being because the image is inverted.

An alternative formulation of this equation, relating object and image distances, gives us three very important equations for object and image distances in terms of the magnification

$$l = f\left(1 - \frac{1}{M}\right) \qquad (11.4)$$

$$l' = f(1 - M) \qquad (11.5)$$

and, considering figure 11.3 and the above two equations

$$\text{OO}' = f\left(2 - M - \frac{1}{M}\right) + \text{PP}' \qquad (11.6)$$

These three important equations are summarised at the top of figure 11.3 for completeness.

Although these equations do not look very exciting stated bluntly here, they are in daily application for the optical engineer. For example, if a photocopying machine is set up for a magnification of –0.5 (half scale, inverted image) with a lens of focal length 250 mm which has a principal point separation of 5.2 mm, the object to image distance will be (from equation 11.6)

$$\mathrm{OO'} = 250\left(2 + 0.5 + \frac{1}{0.5}\right) + 5.2 = 1130.2\ \mathrm{mm}$$

But if a service engineer tries to fit a lens of a focal length that is 1.5 per cent short, what magnification will the machine work at if the object and image are kept fixed, and how far will the lens mounting have to move?

To calculate the magnification we have to rearrange equation 11.6 as follows

$$M = 1 - \frac{\mathrm{OO'} - \mathrm{PP'}}{2f} \pm \sqrt{\left(\frac{\mathrm{OO'} - \mathrm{PP'}}{2f} - 1\right)^2 - 1} \qquad (11.7)$$

which gives us

$$M = -2.0901 \text{ or } -0.4784$$

Obviously it is the second value here that is relevant, and this shows that the reproduction ratio will be 47.84 per cent instead of 50 per cent.

The original object distance was

$$l = 250\ \mathrm{mm}\left(1 - \frac{1}{-0.5}\right) = 750\ \mathrm{mm}$$

whereas the new value is

$$l = 250\ \mathrm{mm} \times 0.985 \times \left(1 - \frac{1}{-0.4784}\right) = 760.987$$

So the lens mounting would have to move away from the object by a distance of 10.987 mm.

Paraxial raytracing

We now come to probably the single most important tool the optical calculator has: the tracing of paraxial rays. These rays are called paraxial because they are only strictly valid close to the optical axis.

The practical engineer generally has a mistrust of anything that smacks of approximation or which has an aura of being a theoretical abstraction and certainly, because of their restriction to the infinitesimal tube surrounding the optical axis, paraxial rays do have this aura of a theoretical abstraction; but this should not put the aspiring raytracer off. Paraxial rays are the only rays that can be used to calculate precise focal lengths and principal point positions, since they are the rays that set up the object and image position for tracing finite rays; they are the key to making carefully controlled changes to an optical system during design adjustment and they can be used to derive all sorts of useful formulas, as we shall see.

It is usual at this point in the discussion of paraxial rays to derive the raytrace equations but, as there are many sources of that information and as it would be an unnecessary digression, we shall content ourselves with merely stating them in a form that is directly of use to the applications of interest to us as optical engineers.

The equation that enables us to calculate the direction of a ray after refraction is known as the refraction equation

$$\boxed{u' = \frac{hc(n - n') + nu}{n'}} \tag{11.8}$$

where the symbols have the following meaning:

u' = Angle of the ray after refraction.
u = Angle of the ray before refraction.
h = Height of the ray at the surface.
c = Surface curvature.
n = Refractive index of the optical medium before the surface.
n' = Refractive index of the optical medium after the surface.

The diagram of figure 11.4 shows all these quantities in their positive form to clarify the sign convention that applies. A ray that is higher on the right-hand side of the diagram has its angle u positive. A surface whose centre of curvature is to the right has a positive curvature.

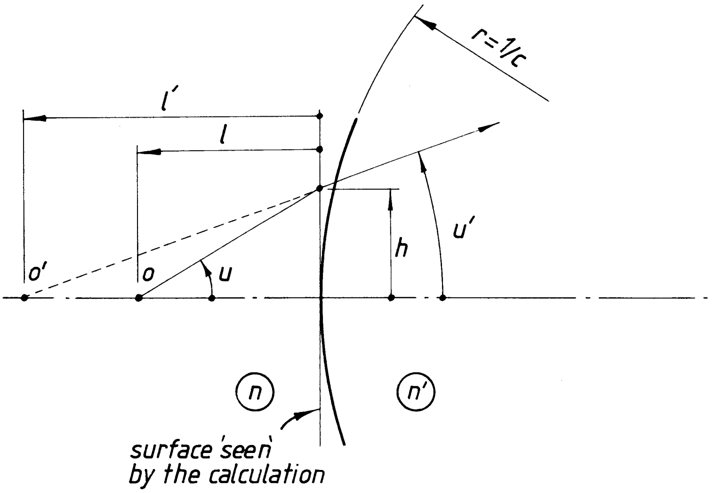
Also shown in figure 11.4, the equation for the position of the image l' is

$$l' = -\frac{h}{u'} \tag{11.9}$$

When starting to trace a ray through an optical system we frequently have the distance of the first surface from the object plane (often negative, as shown in figure 11.4) and, under these circumstances, we can choose some value for u, and then calculate the ray height at the surface, as:

$$h = -lu \tag{11.10}$$

Having calculated u' we can now trace the ray on to the next surface using the



$$u' = \frac{hc(n-n') + nu}{n'}$$

$$l' = -\frac{h}{u'}$$

Figure 11.4 Paraxial refraction

transfer formula

$$\boxed{h_{+1} = h + du'} \qquad (11.11)$$

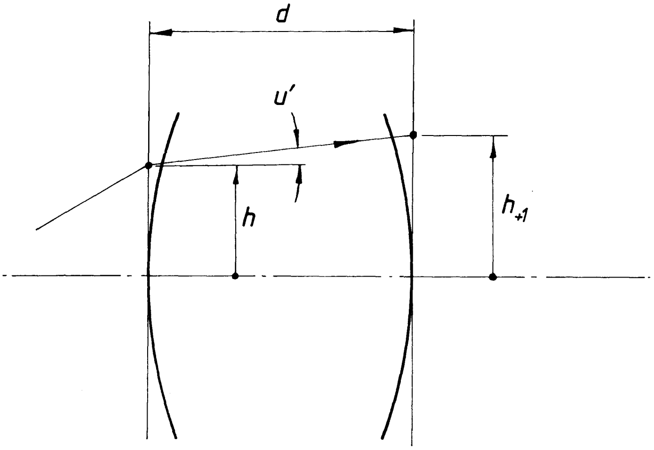
The symbols used in this equation are explained in figure 11.5.

Having calculated h_{+1} we have completed one cycle of the raytracing, this cycle is then repeated for each surface through the system until the ray emerges in the image space.

The values of u and h that are used require some comment. Although the paraxial raytracing equations apply only for rays travelling very close to the optical axis, we may use any values of u and h that we choose because the equations themselves take the necessary precautions to keep the results valid! Because of this it is common practice to trace paraxial rays at angles and heights that represent true finite rays; indeed, paraxial ray surface intersection information may be used to calculate approximations to aberrations, and in these circumstances it is important to trace paraxial rays with appropriate values of h and u. We shall not consider the use of paraxial rays to calculate aberrations in this way because it is conceptually more straightforward to consider aberrations calculated with finite rays.

We shall however now show how paraxial rays are used to analyse the focal properties of real lenses, and later show how they may be used to derive some useful equations.

First, the analysis of a real lens: figure 11.6 shows the optical prescription



$$h_{+1} = h + du'$$

Figure 11.5 Paraxial transfer

of a photographic objective, a venerable design as it happens, being one of the very first photographic lenses corrected for astigmatism, designed by H. Dennis Taylor of Cooke Troughton and Simms in 1895.

The prescription shown in figure 11.6 is a direct scaling of the data in the patent, which should have a focal length of precisely 200 mm. As the relative aperture is $f/4$ we have

$$h_1 = 25 \text{ mm} \quad \text{and} \quad u_1 = 0.0$$

and using equations 11.8 and 11.11 at each surface we find that for this input ray the height at the last surface is

$$h_7 = 20.06304 \text{ mm}$$

and the ray angle after the last surface is

$$u'_7 = -0.124614$$

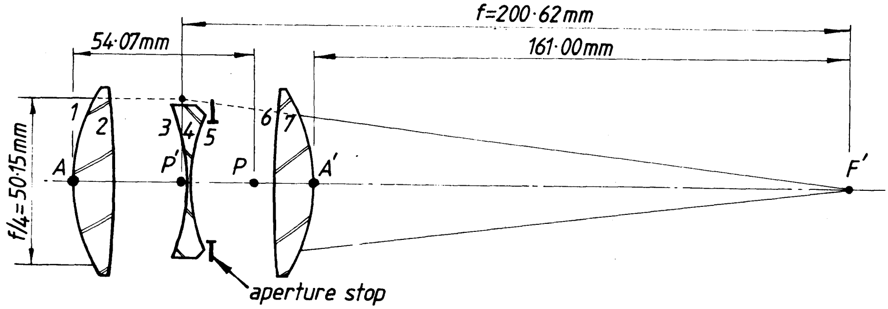
Thus the focal point is at a distance

$$l'_7 = 161.002 \text{ mm}$$

and the effective focal length is given by using equation 11.9 in a new fashion

$$f = -\frac{25}{-0.124614} = 200.62$$

which is sufficiently close to 200 mm to confirm that the data were prepared correctly, and which allows us to locate the rear principal point 200.62 mm from the focal point.



no.	r	ø
1	52·72	56·4
2	-301·40	56·4
3	-59·54	46·6
4	48·30	37·0
5	∞	35·2
6	301·40	56·4
7	-52·72	56·4

d	n_D
11·8	1·5108
21·8	1·0
0·4	1·6042
6·0	1·0
19·0	1·0
11·8	1·5108

Figure 11.6 H. Dennis Taylor's 'Cooke' triplet, from British Patent 15107 (1895) scaled to a focal length of 200 mm

The other information that is used from the tracing of this ray is the radius of the aperture stop

$$\text{radius of aperture stop} = h_5 = 17.564 \text{ mm}$$

As the final effective focal length came out as 200.62 mm, we might refine the value of the aperture stop radius as follows

$$\text{refined aperture stop radius} = 17.564 \times \frac{200.62}{200.00} \text{ mm}$$

$$= 17.618 \text{ mm}$$

By turning the lens around and tracing the same ray we (thankfully!) calculate the effective focal length as 200.62 mm again, and find that the front principal point is 54.07 mm inside the objective, so the principal points are 'crossed' and

$$PP' = -22.89 \text{ mm}$$

This information, combined with the use of equations 11.4, 11.5 and 11.6 allows us to position object and image planes at the correct distances from the lens for any chosen magnification, prior to finite ray raytracing for the determination of aberrations.

We have skipped rather lightly over the actual labour of the raytrace calculations. Although they are straightforward once one has mastered them, the first few surfaces are unexpectedly laborious for the novice and it is to be expected that many mistakes will be made at first, until equations 11.8 and 11.11 are absolutely familiar. If there is a programmable calculator or small computer available the repetitive nature of the cyclic use of equations 11.8 and 11.11 lends itself admirably to the writing of a small program to minimise the fatigue!

So this is how we use paraxial raytracing to determine focal lengths and principal point positions prior to locating the object and image planes for a given magnification. As we have already indicated, however, this is not the only way that the paraxial raytrace equations are of value, and we shall now use them to derive formulas for the focal length of a simple thick lens component and the positions of its principal points.

If we specify a single thick lens component by its two surface curvatures c_1 and c_2, its centre thickness t and its refractive index n, we can set down the following relationships using equations 11.8 and 11.11 to trace a ray with $h_1 = 1.0$ and $u_1 = 0.0$.

Applying equation 11.8 at surface 1

$$u_1' = \frac{c_1(1-n)}{n}$$

Applying equation 11.11 between surfaces 1 and 2

$$h_2 = 1 + \frac{tc_1(1-n)}{n}$$

Applying equation 11.8 at surface 2

$$u_2' = \left(1 + \frac{tc_1(1-n)}{n}\right)c_2(n-1) + \frac{nc_1(1-n)}{n}$$

and thus, because h_1 was 1.0 and u_1 was 0.0, we have

$$\text{effective focal length} = f = -\frac{1}{u_2'}$$

$$= \frac{1}{(n-1)\left(c_1 - c_2 + tc_1c_2\frac{(n-1)}{n}\right)} \qquad (11.12)$$

Similarly, using equation 11.9 at surface 2 we have

$$A'F' = -\frac{h_2}{u_2'}$$

or

$$\mathrm{A'F'} = \frac{1 + \dfrac{tc_1(1-n)}{n}}{(n-1)\left(c_1 - c_2 + tc_1c_2\dfrac{(n-1)}{n}\right)}$$

And because

$$\mathrm{A'P'} = \mathrm{A'F'} - f$$

we have

$$\mathrm{A'P'} = \frac{tc_1(1-n)}{n(n-1)\left(c_1 - c_2 + tc_1c_2\dfrac{(n-1)}{n}\right)}$$

and hence

$$\mathrm{A'P'} = \frac{tc_1(1-n)}{n}f \tag{11.13}$$

and by implication

$$\mathrm{AP} = \frac{tc_2(1-n)}{n}f \tag{11.14}$$

where A′P′ is measured from A′ and is therefore negative when P′ is to the left of A′, and AP is measured from A so that, if P is to the right of A, AP is positive.

PP′ is the quantity that is used in the equation for the object to image distance (equation 11.6) and from equations 11.13 and 11.14 we see that

$$\mathrm{PP'} = t + \mathrm{A'P'} - \mathrm{AP} \tag{11.15}$$

This relationship is shown in figure 11.7, where a thick lens component is shown that has both AP and A′P′ positive to clarify the derivation of equation 11.15.

The beginner in optical calculation who has a background in engineering usually has some trouble with mathematical signs and will be inclined to try and use positive values for as many quantities as possible. This should only be a temporary phase and as he gains more practice the important information revealed by the + and – symbols should become a source of pleasure, the worker noting the systematic consistency of the information emerging from the calculations as the raytracing proceeds.

The triumphal importance of signs can perhaps best be demonstrated by applying some of the equations that we have developed to an apparently inappropriate case; by arranging the signs to codify the differences between the standard situation and the special situation, we shall see just how powerful the equations are.

Consider the astronomical telescope shown in figure 11.8. What is its focal length and where is the image plane?

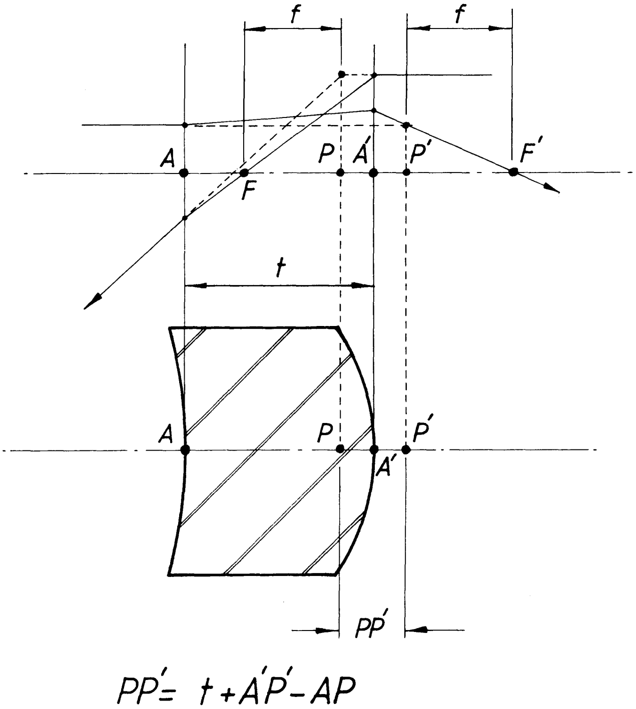

f
f
A
P
A′
P′
F′
F
t
A
P
P′
A′
PP′
PP′= t+A′P′−AP

Figure 11.7 Value of PP′

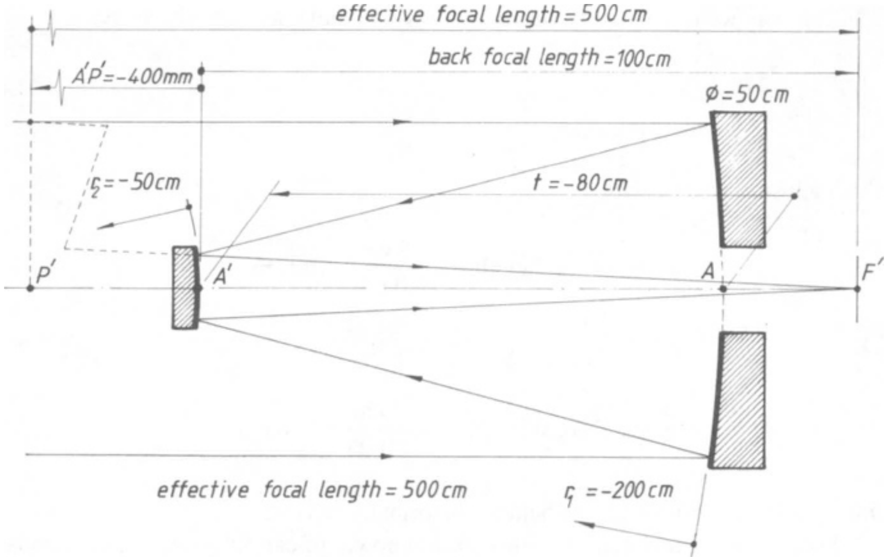

effective focal length = 500 cm
back focal length = 100cm
A′P′=−400mm
ø=50cm
r₂=−50cm
t =−80cm
P′
A′
A
F′
effective focal length = 500cm
r₁ =−200cm

Figure 11.8 Paraxial analysis of a 0.5 m astronomical telescope

First, if we apply the paraxial raytracing equations (equations 11.8 and 11.11) to a ray incident on the primary mirror from a star at left-hand infinity, we see that

$$h_1 = 25 \text{ cm and } u_1 = 0$$

When we come to apply equation 11.8 the question immediately arises – how do you cope with reflecting surfaces? The answer may come as a surprise to a novice: because refractive index may be defined as the ratio of the *velocity* of light in vacuum to the *velocity* of light in the optical medium concerned, and because velocity is a vectorial quantity, light travelling left to right 'sees' a positive refractive index, whereas light travelling right to left 'sees' a negative refractive index. Thus, after reflection our ray will be travelling right to left and must therefore be in a medium (air) whose refractive index is negative! In this way we may apply equation 11.8 as long as we remember that

$$n = 1.0 \text{ and } n' = -1.0$$

At the secondary mirror the ray is reflected and again travels from left to right, so at that surface

$$n = -1.0 \text{ and } n' = 1.0$$

Just as when the light travels from right to left the refractive index changes its sign, so too does the separation and, thus, when we apply equation 11.11 to the transfer of the ray from the primary mirror to the secondary, we use a negative value of d.

In this way we trace the ray through the system until we have the values

$$h_2 = 5 \text{ cm}$$

$$u_2' = 0.05$$

which allow us to calculate

$$\text{effective focal length} = -\frac{25 \text{ cm}}{-0.05} = 500 \text{ cm}$$

and

$$\text{the 'back' focal length} = -\frac{5 \text{ cm}}{-0.05} = 100 \text{ cm}$$

Thus, the image plane is 20 cm behind the primary mirror.

What is a more lucid demonstration of the power of carefully derived equations is for us to reach the above results by using equations 11.12 and 11.13.

To use equations 11.12 and 11.13 we must note that

$n = -1$ (the refractive index between surfaces 1 and 2)
$c_1 = -0.005$ (primary mirror)
$c_2 = -0.02$ (secondary mirror)
$t = -80$ cm (separation between the two mirrors)

which, with equation 11.12 immediately yields

effective focal length = 500 cm

and with equation 11.13

$A'P' = -400$ cm

thus making

'back' focal length = 100 cm

as before.

So, an equation derived for a simple lens can be used to analyse an apparently completely different system as long as the calculation can be made to 'see' the differences in a systematic scheme of notation and with due regard to the mathematical signs that are appropriate to each quantity.

Incidentally, although we have traced the ray to calculate the focal length without any regard to any mirror asphericities, this does not in any way invalidate the calculation. The ray we have traced is 'paraxial' and is defined only in the infinitesimal region close to the optical axis, where the asphericities have no effect. In fact paraxial calculations are probably more valid in this situation than would normally be the case, because the asphericities applied to the mirror surfaces serve to bring the finite rays to the paraxial focus, whereas, in the case of purely spherical surfaces, there are almost always aberrations at finite apertures which pull the focal point away from the paraxial position.

Some care has been taken in figure 11.8 to indicate the signs of the various quantities by drawing the witness arrows with a single arrow head, showing the direction in which each quantity is measured.

12

Optical Specifications

There are a surprisingly large number of quantities that must be specified to identify what type of optical system is required in any particular situation and it is the purpose of this chapter to itemise these specification features and indicate the implications of each item for the optical engineer.

We shall start with a simple list of the quantities that must be specified:

(1) Focal length, object to image distance and magnification, or simply magnification for a compound instrument.
(2) Aperture: resolution or working spatial frequency and photometric requirements.
(3) Field of view in either angular or linear terms and vignetting.
(4) Chromatic bandwidth.
(5) Mechanical position and size.
(6) Aperture position.

If we now consider some specific examples it should become clear why each of these specification items is important.

Returning to an example that was considered in the previous chapter, we will examine more closely the case of the 50 mm lens intended for the familiar 35 mm still camera and review the importance of each of the above specification items, along with their importance for other key optical instruments.

(1) Focal length and magnification

The focal length of a camera lens determines the scale of the image on the film; thus, a 100 mm focal length lens forms an image that is magnified twice relative to that formed by a 50 mm lens.

The magnification of a telescope is most naturally expressed as the simple ratio of the angle subtended at the eye by any specific distant object with and without the telescope. This angular magnification ratio is given by the ratio of the focal length of the objective to the focal length of the eyepiece or, what amounts to the same thing, the diameter of the objective aperture divided by the diameter of the exit beam entering the eye.

The simple magnifier or eyepiece 'magnifies' by allowing the observer's eye to focus on objects closer than would normally be the case and thus the object appears larger. In this way, if we assume that 250 mm is a normal minimum viewing distance and an object viewed by a simple magnifier is placed in the focal plane of the lens, then the magnification ratio is given by 250 mm/*f* mm, so that a 20 mm lens has a magnification of X12.5.

A compound microscope uses an eyepiece in the above fashion, but also has an objective that forms a real magnified image of the object according to the normal rules of relay magnification, which the eyepiece can then be used to examine. In this way, the magnification of the compound instrument is arrived at by multiplying the relay magnification of the objective by the simple magnifier type of magnification provided by the eyepiece.

(2) Aperture: resolution, working spatial frequency and photometric requirements

Clearly, the aperture of a lens is of fundamental specification importance; however, it is often treated in a casual fashion, without due regard to the details of its function.

The typical modern 50 mm camera lens is usually given a maximum relative aperture of $f/2$, $f/1.4$ or even greater, with a view to allowing the photographer to take photographs under conditions of low light level. At any particular focal length the photometric brightness of the image is proportional to the area of the lens aperture (as you might expect) and, as the relative aperture is a simple expression of the diameter of the effective aperture ($f/2$ = focal length ÷ 2 = diameter), we see that the image illumination is proportional to the square of the relative aperture (because the area of a circle is $\pi D^2/4$). Thus, an $f/2$ lens collects twice as much light as an $f/2.8$ lens because

$$\left(\frac{f}{2}\right)^2 = 2\left(\frac{f}{2.8}\right)^2$$

and going the other way, an $f/1.4$ lens collects twice as much light as an $f/2$ lens.

So we can see why the photographer is keen to have a lens with as large a diameter as possible relative to the focal length; but this is not the whole story, of course, and as all readers of this book will know, it is not possible to have a lens with a large relative aperture without paying for the manufacture of larger and more complicated components and, what is more to the point, without suffering the increased effects of aberrations.

Most photographic film can barely handle 100 cycles per mm and it is much happier at 50 c/mm, although even at that lower spatial frequency the effects of grain are often objectionable (grain and resolution are separate considerations). On the other hand, a lens can theoretically resolve an angle of

$$\text{angular resolution} = \frac{1.22\lambda}{D} \tag{12.1}$$

where this angle is in radians, λ is the wavelength and D is the diameter of the lens. This formula is the celebrated Airy–Rayleigh diffraction resolution formula which is to be found in any textbook on optics. The angular resolution is related to linear resolution on the film through the focal length; thus

$$\text{resolution at the film} = \frac{1.22\lambda}{D} f\,(\text{mm})$$

or in terms of c/mm

$$\text{resolution at the film} \simeq \frac{D}{1.22\lambda f}\ \text{c/mm}$$

where this last equation is only approximate because equation 12.1 applies only to single point sources and not the sort of grating object assumed when one refers to c/mm.

So, an $f/2$, 50 mm photographic lens has a diameter of 25 mm, green light has a wavelength of 0.00055 mm and the resolution at the film can be 745 c/mm!

Even if we say that only approximately one-third of this bandwidth is practically achievable, we still have the potential for about 250 c/mm. However, the aberrations of high aperture photographic lenses can easily bring the practical resolution down to 50 c/mm, especially off-axis and indeed, most wide aperture photographic lenses are seriously limited by aberrations off-axis at 50 c/mm when they are used at their maximum aperture.

Photographic lenses are, of course, seldom used at their maximum aperture and it is this fact that usually saves the situation, but a lens design that is balanced for $f/1.4$ will not perform as well at $f/2.8$ as the same lens construction balanced for $f/2.8$, and the serious photographer who is not intending to do low light level photography with a particular lens should look carefully at his requirements and decide whether they would be better served by a lens designed for the preferred aperture.

In passing, it is worth noting that the horizontal bars of a capital letter E in the average paper-backed novel are something like 1 mm apart and, if such a paper-backed novel is viewed at a distance of 50 x the focal length of the lens (2.5 m), the bars of a capital letter E will be reproduced at approximately 50 c/mm on the film while the smaller, more fussy letters will represent higher spatial frequencies. A 50 mm camera lens on a 35 mm camera focused on 2.5 m that can record a microscopically readable reproduction of the page of a paper-back novel placed anywhere in its field of view is rather good! Certainly, few commercial photographic lenses would pass this test at full aperture, but might do so as they are stopped down. At $f/8$, our 50 mm lens has a theoretical resolution of 186 c/mm and, if we assume as before that only about one-third of that bandwidth is practically realisable, we can expect the lens only to record something like 62 c/mm, which is certainly not enough to pass the paper-back test unless one is happy to read only capital letters!

Compound optical instruments, such as telescopes and microscopes, and the subassemblies that constitute the objectives and eyepieces of these instruments have their apertures specified in different fashions which reflect the different purposes to which these instruments are put.

Hand-held telescopes and binoculars should not make dimly lit scenes appear any dimmer and this means that the effective aperture of the observers's eye should not be restricted by the aperture of the instrument.

The aperture of a telescope at the eye is a demagnified image of the objective, demagnified by the angular magnification of the instrument. This aperture is called the exit pupil, or the Ramsden disc. In the case of a pair of binoculars with a 7 x 50 specification the angular magnification is X7, and the objective diameter is 50 mm; thus, the aperture of the instrument at the eye will be 50 mm ÷ 7 = 7.14 mm, which is big enough to cover the pupil of the human eye under all normal conditions. On the other hand, a pair of 12 x 40 binoculars will have an exit pupil only 3.3 mm in diameter, which is not large enough to use the instrument under dim conditions.

It is instructive to take this consideration of the aperture of hand-held telescopes a bit further. If the objectives of a pair of 7 x 50 binoculars have a focal length of 200 mm, their relative aperture will be 200 mm/50 mm = 4, and considering that such an objective will usually be a simple cemented achromatic doublet, we may expect its performance to be limited by aberrations, especially off-axis. The focal length of the eyepiece of this instrument will be 200 mm/7 = 28.57 mm and thus, again, its relative aperture will be 28.57 mm / 7.14 mm = 4 (of course, if you think about it!) and, depending on its optical construction and the field angle of the instrument, so this may or may not be a demanding optical specification.

The aperture of an astronomical telescope determines the light gathering power and angular resolution, according to equation 12.1 and thus they are referred to as '0.5 m', '200 inch' and so on. Practically, the theoretical resolution predicted by equation 12.1 cannot be reached because of atmospheric turbulence and constructional errors, but the light flux collected by the aperture is proportional to its area.

Microscope apertures are also specified in terms that are related to their resolving power, but in this case the resolution is expressed in terms of the linear separation between two points on the microscope stage that can just be resolved, and this is given by

$$\text{linear resolution} = \frac{0.61\lambda}{n \sin u} \qquad (12.2)$$

where λ is again the wavelength, n is the refractive index at the object and u is the semi-angle of the cone of rays filling the aperture from the object point.

This resolution equation also comes from the work of Airy and Lord Rayleigh and is in effect the same equation as 12.1. To avoid digression we would again refer the reader to any of the standard optical textbooks, which all deal in some detail with this most exciting and universal formula.

Using equation 12.2 we discover that, for a microscope objective with $u = 40°$ and $n = 1.0$ (air) used with green light, which has $\lambda = 0.00055$ mm

$$\text{linear resolution} = 0.00052 \text{ mm}$$

which corresponds to something like 1900 c/mm.

The quantity $n \sin u$ that appears on the bottom of equation 12.2 is known as the numerical aperture or NA of the microscope objective and it is this quantity that is used to specify the aperture. If, as in this example, $u = 40°$ and $n = 1.0$, then the NA = 0.643. In terms of f numbers, because the effective aperture diameter of such an objective is given by $2f \sin u$ (that is, $1.286f$) then the f number will be

$$\frac{f}{1.286f} = 0.778$$

If such an objective is used to form a magnified image on normal photographic film, then the linear resolution should, for comparison purposes, be magnified to approximately 0.02 mm (50 c/mm); that is, the magnification should be 0.02 mm/0.00052 mm which is X38.5. If, on the other hand, the objective is used with an eyepiece as is more usual, the linear resolution must be magnified into the common image plane of the objective and eyepiece so that the eye sees it subtending approximately 1 minute of arc, which is generally accepted as the practical angular resolution limit of the human eye. (Equation 12.1 gives 0.33 minutes of arc for an eye with a pupil diameter of 7 mm, but the eye pupil is almost always smaller than that and the aberrations of the eye do in any case reduce the resolution limit. Retinal structure, which has been blamed for this shortfall, is not responsible because the neural and physiodynamic mechanisms of visual perception seem to be quite capable of separating retinal grain from image information.) If the eyepiece has a focal length of 20 mm, which is fairly typical, then 1 minute of arc corresponds to 0.0058 mm at the common intermediate focal plane and the objective magnification should be 0.0058/0.00052 = X11.2.

In practice, it is usual to use a greater magnification than this to avoid compromising the hard-won image quality of the intermediate image, and in fact X40 is a more usual magnification for such an objective.

Figure 12.1 is a graphical summary of the aperture characteristics of a photographic lens, an astronomical telescope, a hand-held telescope and a microscope.

(3) Field of view and vignetting

A lens for a 35 mm still camera (so called because the film stock is 35 mm wide) has to cover an image 24 mm x 36 mm. The corner of the image is 21.6 mm away from the optical axis and the angular extent of the semi-field of view is given by

$$\text{semi-angular field} = \pm \tan^{-1}\left(\frac{21.6 \text{ mm}}{f \text{ mm}}\right)$$

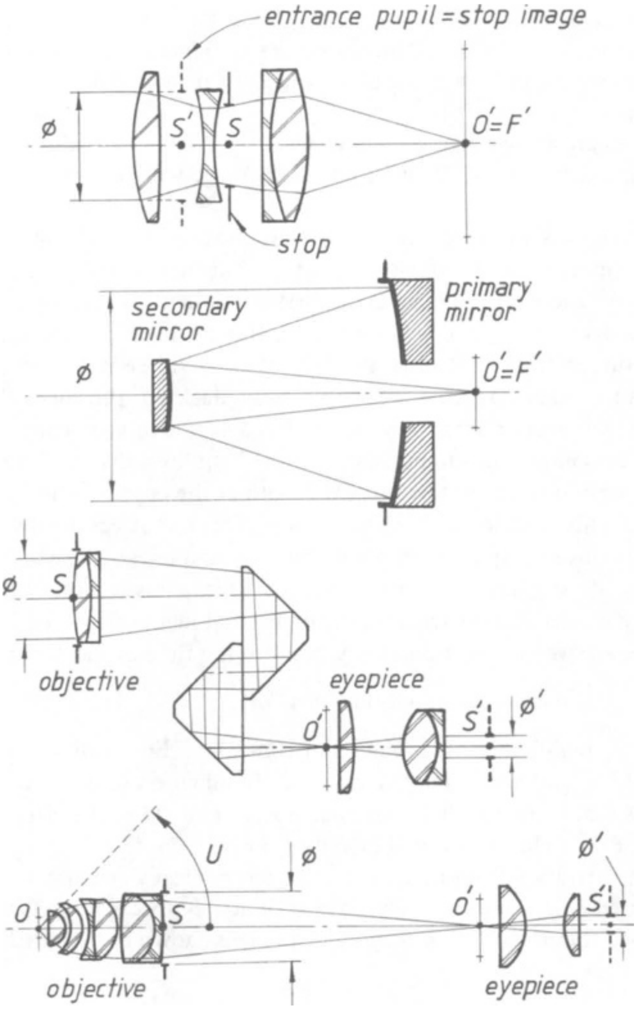

entrance pupil=stop image
ø
S'
S
O'=F'
stop
secondary mirror
primary mirror
ø
O'=F'
ø
S
objective
eyepiece
O'
S'
ø'
U
ø
ø'
O
S
O'
S'
objective
eyepiece

Figure 12.1 Apertures in various optical instruments

Thus, a 50 mm lens covers ± 23.4°, a 200 mm telephoto lens covers ± 6.2° and a wide angle lens with a focal length of 20 mm covers ± 47.2°; in short the angular field of view of a lens is the angle subtended by the object at the front principal point, or by the image at the rear principal point.

In the case of an eyepiece, the same applies; it is the angle subtended by the field stop at the appropriate principal point. So, for example, if an eyepiece has a focal length of 20 mm, and a field stop with a diameter of 20 mm, it is covering an angular field of view of $\pm \tan^{-1} (10/20) = \pm 26.6°$. Such an eyepiece, as we have seen, may have a relative aperture of *f*/4, and because the aperture stop is remote from the lens components such an eyepiece can be a difficult optical design task if good quality images are required.

The 200 inch astronomical telescope on Mount Palomar has an *f*/3.3 primary mirror, so the focal length is 200 inches x 3.3 = 660 inches. If such a mirror is used with a 60 mm square photographic plate, the angular field will be $\pm \tan^{-1}$ (42.4 mm/16764 mm) = ± 0.14°.

A typical microscope objective has a value of $l' = \mathrm{P'O'} = 160$ mm, so that if the field stop has a diameter of 20 mm the field coverage will be $\pm \tan^{-1}$ (10/160) = ± 3.6°.

The fields of view we are discussing here are those over which the image quality is required to meet some specification or other, but there is also a more obvious requirement for the image to exist at all; that is, for light to actually reach all points of the image. To take a stupid example, if the film aperture in a camera has a smaller aperture in front of it, then the field of view will be restricted or vignetted by this aperture. Such vignetting will completely black-out the edges of the image but, to a lesser or greater extent, every lens has a degree of vignetting: either the edges of the lens mounting obscure some of the light, as shown in figure 12.2, or the inherent obliquity and extended path length at the edges of the field of view will reduce the illumination at the image plane. This last effect involves four cosine factors (inverse square law, pupil obliquity and image plane obliquity) and for lenses that do not have any lens components far removed from the aperture stop, nor any mechanical obstruction of the type shown in figure 12.2, we can estimate the relative illumination at any point in the field of view as being

$$\text{relative illumination} = \cos^4 \bar{u}$$

where $\bar{u}$ is the semi-field angle at the point concerned. For example, such a lens, covering ± 40° would have a relative marginal illumination of $\cos^4 40° = 0.34$, which means that if the lens has a nominal aperture of *f*/2.8, the effective aperture at the edge of the field of view will be only *f*/4.8!

There are aberrational advantages in using mechanical vignetting to trim off badly aberrated portions of the light passing obliquely through the lens. It is not difficult to see that the off-axis imagery of the lens shown in figure 12.2 can be

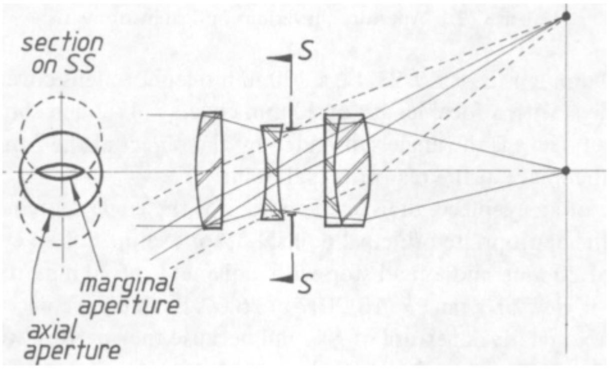


Figure 12.2 Mechanical vignetting

of a relatively high standard when only such a small portion of the aperture is used at the edge of the field of view.

When it is imperative that the image illumination at the edge of the field of view is maintained at the same level as the axis, considerable additional cost has to be incurred by adding negative components at some distance from the aperture stop. Figure 12.3 shows a conventional wide angle photographic lens and, on the same scale, a wide angle photographic lens of the same focal length which has compensation for vignetting.

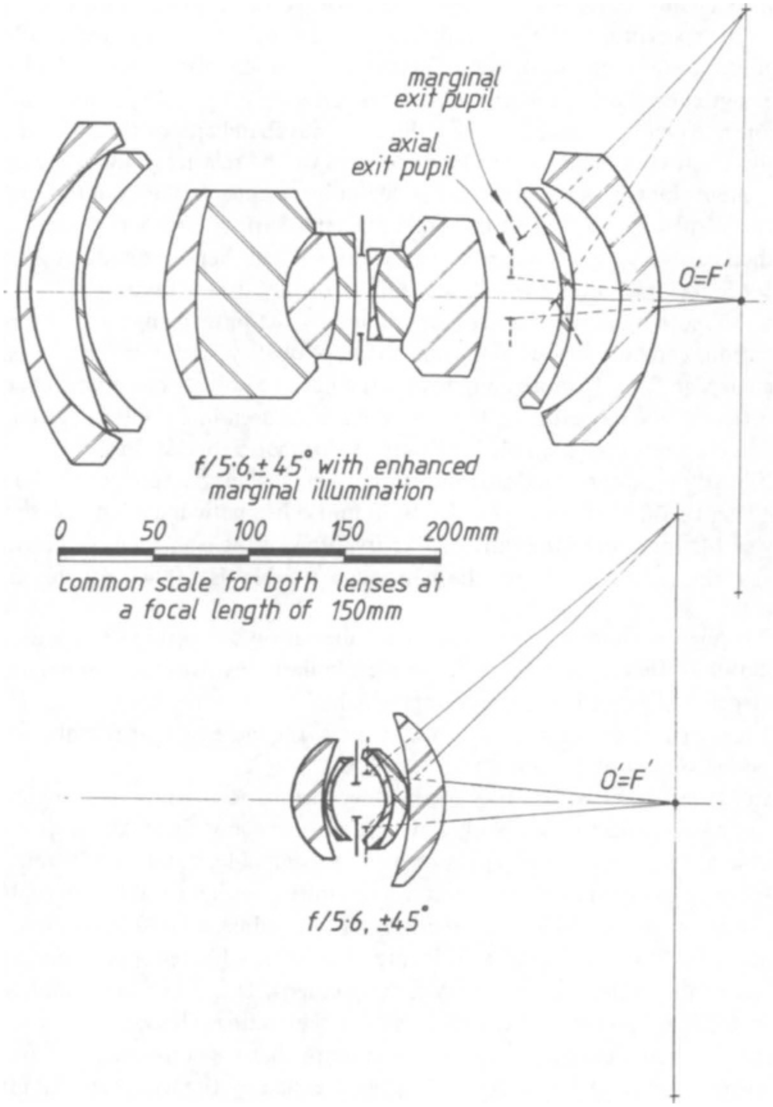

marginal exit pupil
axial exit pupil
O'=F'
f/5·6, ± 45° with enhanced marginal illumination
0 50 100 150 200mm
common scale for both lenses at a focal length of 150mm
O'=F'
f/5·6, ±45°

Figure 12.3 Compensation of vignetting

(4) Chromatic bandwidth

The human visual system can detect wavelengths from approximately 400 nm (nm = nanometres, 1 nm = 10^{-9} m) which is deep violet, to approximately 700 nm which is deep red, with the well-known bell-shaped distribution of sensitivity that peaks in the yellow–green region (555 nm) in bright light and in the blue–green region (510 nm) in dim light.

Various combinations of illuminant, system transmission and detector response produce a whole range of overall spectral sensitivities, from the ultra violet through the visible spectrum to the infrared. Even more exotic wavebands exist, of course, including X rays at the short wavelength end and millimetre waves at the long wavelength end. Each waveband has associated with it optical systems with appropriate characteristics. At the millimetre waveband end of the spectrum where the surface texture of the optical components can be relatively gross, the optical components may be made from expanded polystyrene granules and the surfaces may be shaped with a file! At the other extreme, surfaces for X-ray work must be polished to a very high standard of surface finish and then used only at grazing incidence to foreshorten the hills and valleys of the surface texture.

In the more usual wavebands encountered by the optical engineer, chromatic aberrations can be a serious limitation to image quality, and most optical systems are made significantly more complex by the need to correct chromatic aberration. In particular, the curvature of the optical surfaces used in an optical system that is corrected even for only simple longitudinal chromatic aberration will have significantly greater surface curvatures than a single lens component of the same focal length. Take, for example, the 1000 mm achromatic lens that is designed in chapter 14: the sum of the (unsigned) curvatures of the single lens is 0.0019, whereas the same quantity for the achromatic doublet is 0.0047, roughly 2.5 times as great.

This phenomenon is common to many aberration correction situations; the correction of field curvature, for example, similarly involves the combination of positive and negative lens components which results in a further increase in the total sum of surface curvatures over and above the increase that is required to correct chromatic aberration.

An extremely successful way of avoiding chromatic aberrations completely is, of course, to use reflecting surfaces, which do not have any chromatic dispersion. By direct analogy with the comparison between a simple lens and an achromatic doublet, we can compute the curvature of a mirror with a focal length of 1000 mm. As a concave mirror has a focal length of half its radius, a 1000 mm mirror will have a radius of 2000 mm; that is, a curvature of 0.0005, which is approximately one-quarter of the value of even the simple singlet lens. This is not the complete story, but it does explain some of the success of the reflecting telescope!

The chromatic bandwidth of optical systems that are composed of refractive (and therefore dispersive) components may be extended by the use of special glasses or crystals, which generally have unattractive processing properties, or alternatively

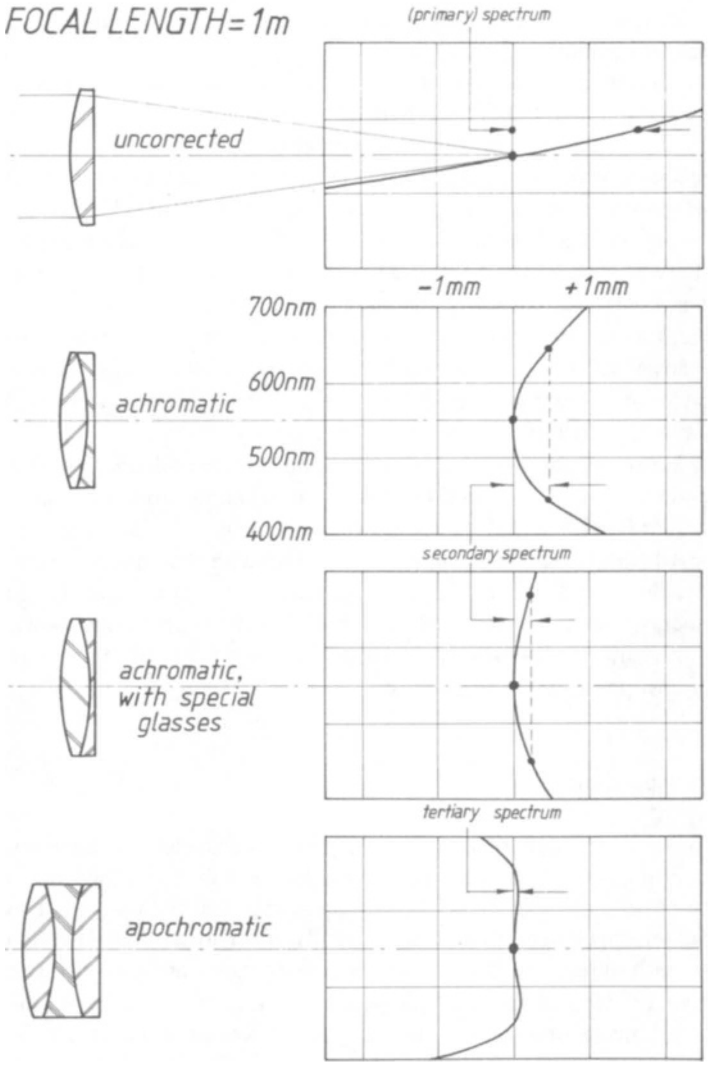

FOCAL LENGTH = 1m
(primary) spectrum
uncorrected
−1mm
+1mm
700nm
600nm
500nm
400nm
achromatic
secondary spectrum
achromatic, with special glasses
tertiary spectrum
apochromatic

Figure 12.4 Different types of chromatic correction

by a considerable increase in complexity. Such refractive optical systems are called apochromatic. Figure 12.4 shows the variation of image plane position (longitudinal chromatic aberration) with wavelength for four different types of chromatic correction.

(5) Mechanical position and size

We have already seen how mechanical size can be strongly influenced by the demands of aberration correction (see figure 12.3 and section (3) above); in general, for a given focal length, the larger a lens is, the greater is the potential that exists for aberrational refinement.

There are frequently other important influences on the layout of optical systems: this may be the requirement for mechanical clearance between the lens and the image plane, or a restriction on the overall length of the system from the image plane to the object end of the hardware. These two design influences result in telephoto or inverted telephoto constructions. A telephoto lens is mechanically shorter than the equivalent conventional lens, whereas an inverted telephoto lens has a greater back clearance between the lens and the image plane than a conventional lens. Obviously, a lens that is mechanically shorter than would occur in the normal course of events has significant advantages where portability is important. Alternatively an inverted telephoto lens which has an enhanced back clearance is of use where a beam splitting prism or a viewfinder reflex mirror is required, or where long working clearance is needed in a microscope or an engineering profile projector.

Figure 12.5 shows some typical telephoto and inverted telephoto lens designs. As can be seen in this figure, inverted telephoto lenses can be embarrassingly bulky relative to their focal length. However, this can actually be an advantage in the case of very short focal length lenses which would otherwise have minute lens components that could be too small for convenient glass processing. For large format cameras, such inverted telephoto lenses and the type of lens shown in the upper half of figure 12.3 represent the most expensive types of photographic lens in terms of cost per unit of focal length.

(6) Aperture position

Our discussion of paraxial raytracing in the previous chapter and the various facets of specification in this chapter has been remarkable so far for rather little mention of the path of off-axis pencils of light passing to marginal field points. The fact is that, having set up a lens at a particular magnification either theoretically or practically, with object and image planes in appropriate positions with respect to the lens, the aperture stop can in principle be placed more or less anywhere between the object and image, or even outside the space between the object and image. Having said this, it must be made clear that the position of the aperture stop does have a profound influence on the aberrational performance and the physical size of the lens components. The lens shown in figure 12.6, for example, may be used with an aperture stop in any position, and then different parts of the lens are involved in forming the image of any particular off-axis image point, depending on where the stop is placed. Obviously, if the stop is placed in contact with the lens, it is the central part of the lens that is used for all image points and the edge of the lens may be removed altogether. As can be seen in figure 12.6, by placing the aperture stop in different positions not only are different parts of the lens illuminated by the characteristic object point but also different aberrations are selected, so moving the precise position of the image and changing its aberrational characteristics.

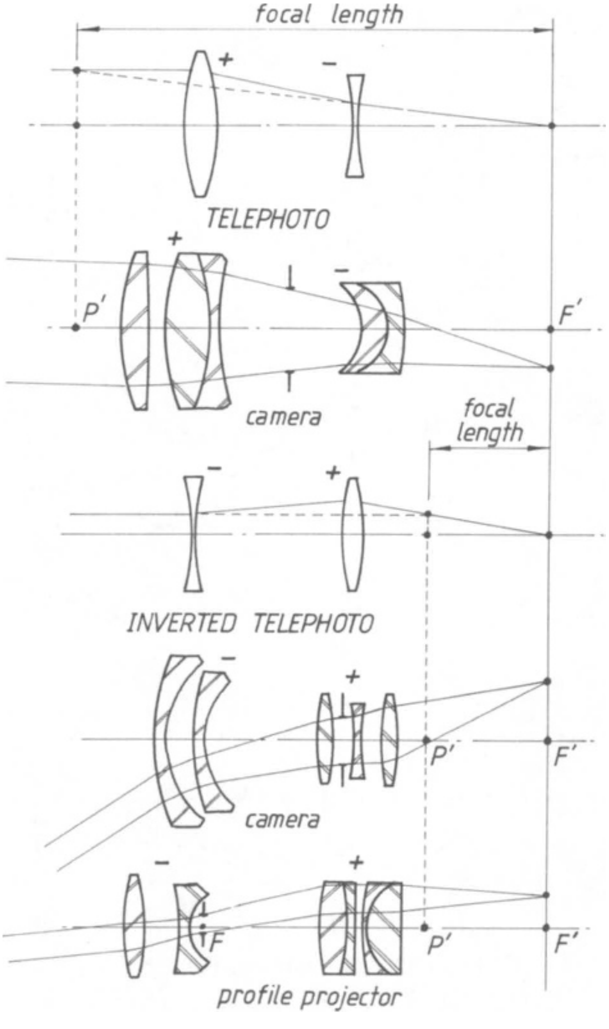

focal length
+
−
TELEPHOTO
+
−
P′
F′
camera
focal length
−
+
INVERTED TELEPHOTO
−
+
P′
F′
camera
−
+
F
P′
F′
profile projector

Figure 12.5 Telephoto and inverted telephoto lenses

The other thing to notice in figure 12.6 is that the diagram at the top of the figure is effectively the same as the diagram at the bottom of the figure, in that the same portion of the lens is used and the same aberrations are operative in both cases. There is however a difference between the two cases; if, for example, the lens is being used with a photographic plate at O′ and an opaque object at O, the practical effect of the stop shown in the lower diagram would be non-existent and the stop would effectively be the edge of the lens, so passing all possible aberrations.

There are two important situations where the aperture stop is remote from lens components. Figure 12.5 illustrates one of these cases, which is the profile projector; in the profile projector, calibrated measurements are made on the screen

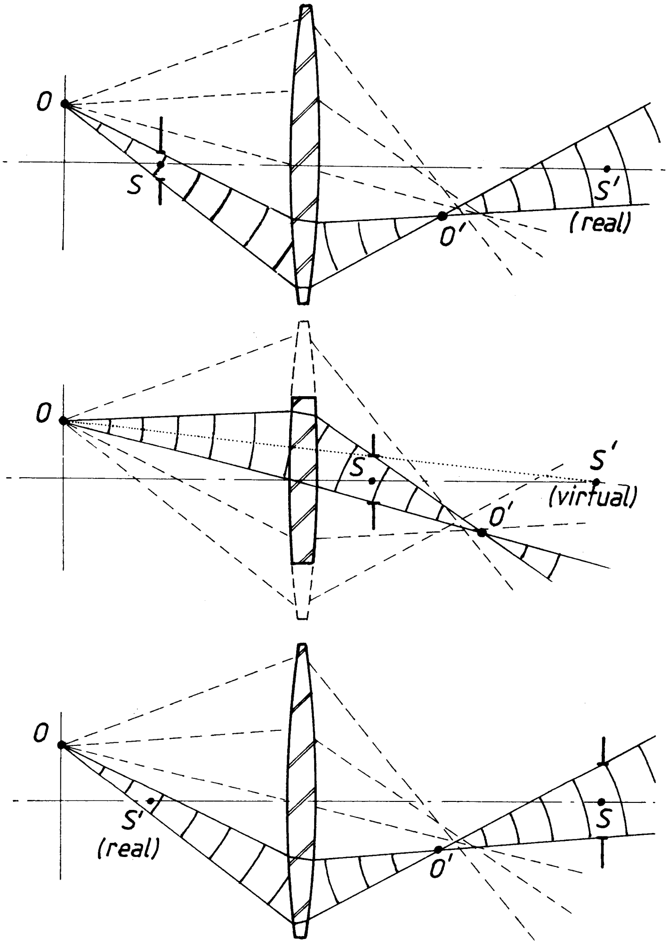


Figure 12.6 Effects of stop position

where the enlarged image is formed, and for the measurements to be reliable the lens must look at off-axis object points ‘square on’, as shown in the ray diagram of figure 12.5. For the profile projection objective to view off-axis object points square on, it is necessary to place the aperture stop at the back focal point, as shown in figure 12.5, and this leads to what is known as the telecentric condition. When a lens is set up with a telecentric stop, the size of the image is unaffected by any error of focusing at the object, so that even though the image might be blurred it will still be of the correct size.

The other situation where the aperture stop is remote from the lens is in compound visual instruments where the aperture stop is at the objective and thus remote from the eyepiece. In such compound visual instruments where there is a real intermediate image, the aperture stop is relayed to the eye position by the eyepiece and, because the focal length of the eyepiece is relatively short compared with the separation between the objective and the eyepiece, the eye position is close to the rear focal point of the eyepiece. Unlike the profile projector, the eyepiece cannot have any optical components on the other side of the (relayed) aperture stop, which makes the correction of oblique aberrations particularly difficult.

13

Aberrations and Their Correction

The job of an optical designer is to decide what construction of lens to use for each optical subassembly in the instrument that is to be designed and then calculate the specific surface radii, diameters, separations, thicknesses and glass types that are to be used in each part of the instrument.

Some parts of this task are relatively straightforward, others require a great deal of detailed numerical work and a considerable amount of skill, and yet others fall into the realm of optical research when particularly ambitious specifications have to be met.

At its simplest level, optical design consists of taking the optical prescriptions of the required subassemblies from the patent literature and scaling them to the required focal lengths. Even this task involves analysing the optical prescriptions concerned to calculate focal lengths, locate principal points, choose diameters, and fit existing optical tooling to the scaled surface radii, in addition to checking that the claims of the patent are not exaggerated!

Analysing the performance of image-forming systems involves calculating aberrations by tracing rays that pass through the optical system at all points of its aperture and which correspond to all field angles. Such rays are not paraxial and they involve the use of trigonometry in the calculation of their paths; because of this, the calculation of the paths of such rays is referred to as trigonometrical raytracing and the rays are referred to as 'trigonometrical' or 'finite' rays.

There are two types of finite rays: meridional and skew. Meridional rays are the rays that are normally drawn in optical diagrams and they lie in the plane containing the optical axis; that is, the plane of the usual cross-section that is shown in optical drawings. Skew rays do not lie in any plane containing the optical axis and do not in general intersect the optical axis or the principal ray (which is the meridional ray that passes through the centre of the aperture to the off-axis field point of interest).

Most of the rays that can be thought of passing through an optical system are skew, a small proportion are meridional and an infinitesimal proportion are paraxial. In terms of value for effort, paraxial raytracing wins hands down, but the aberrational information that can be extracted from a paraxial raytrace is strictly limited, and when it comes to aberration calculations meridian rays are the most important. Skew rays come a poor third – they are laborious to trace (not when you have a computer though!) and give disappointingly little diagnostic aberrational information.

Most aberrations can be adequately described and calculated using meridional rays and we shall now give a short descriptive list of the seven most important 'primary' aberrations by showing the paths of the appropriate meridional rays.

These aberrations are traditionally listed in a particular order, after a brilliant theoretical analysis by the German optician L. von Seidel, who, in the last century, argued that even a paraxial raytrace contains implicit aberrational information and then proceeded to derive the necessary equations which extract that information, equations that are the keystone of any systematic philosophy of optical design to this day. Because of the conceptual inconveniences of presenting von Seidel's equations and their interpretation for practical optical systems, we shall stay with finite meridian rays, but present the aberrations more or less in their traditional order.

1. Spherical aberration

This is the most famous of the aberrations and corresponds to rays that pass through different zones of the aperture coming to a focus at different points along the optical axis, as shown in the first diagram of figure 13.1. The point marked O'_P is the image formed at the focal point by the paraxial region of the lens. The point marked O'_M is the image formed by the margin of the lens.

Spherical aberration may be reduced or eliminated by dividing the focal power between several components, by combining positive and negative lenses or by using non-spherical surfaces. All three methods are in widespread use and some examples are shown in figure 13.2.

The first diagram in figure 13.2 shows a typical condenser system as might be found in a photographic projector. The way this design works is to keep the spherical aberration contribution at each component to a minimum so that the total spherical aberration cannot build up to an unacceptable level. The condenser shown in this diagram consists of three components which will normally have roughly equal powers but which will be 'bent' to different shapes as shown, to achieve the required minimisation of the spherical aberration.

The next two diagrams show how a positive and a negative lens may be combined to correct spherical aberration. The lower of these two diagrams shows how the aberrated ray distribution after the first component is used as a virtual object for the second component, whose shape and focal power are chosen so that its spherical

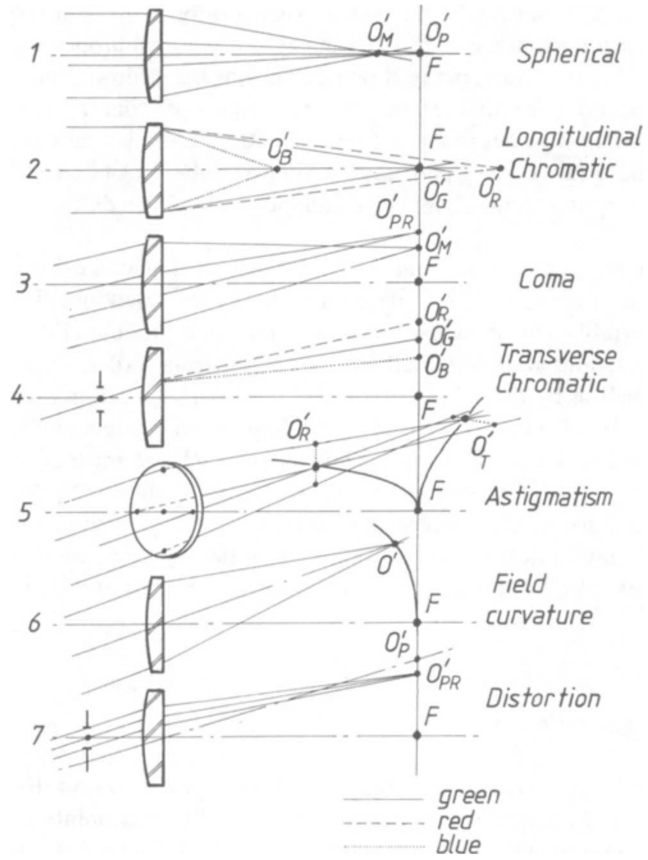

1
O'M
O'P
F
Spherical
2
O'B
F
Longitudinal
Chromatic
O'G
O'R
O'PR
3
O'M
F
Coma
4
O'R
O'G
O'B
Transverse
Chromatic
F
O'R
O'T
5
F
Astigmatism
O'
6
Field
F
curvature
O'P
O'PR
Distortion
7
F
green
red
blue

Figure 13.1 The seven primary aberrations

aberration is exactly equal and opposite to that of the first component. In this type of design where positive and negative components are combined to produce a final combination whose focal power is positive, the individual powers are working against each other and therefore they have to be individually more powerful than a single component doing the same job. The final spherical aberration correction is also different, exact compensation is possible only at one aperture height and at other aperture heights there remains a secondary error, a situation which is not unlike the achromatic correction shown in figure 12.4. Just as in figure 12.4 it is possible to design lenses with a higher order of (apochromatic) correction which has only a tertiary error, so too it is possible to do the same thing with spherical aberration.

The graphs shown on the right-hand side of figure 13.2 give the schematic variation of ray intersection distance along the optical axis plotted against aperture

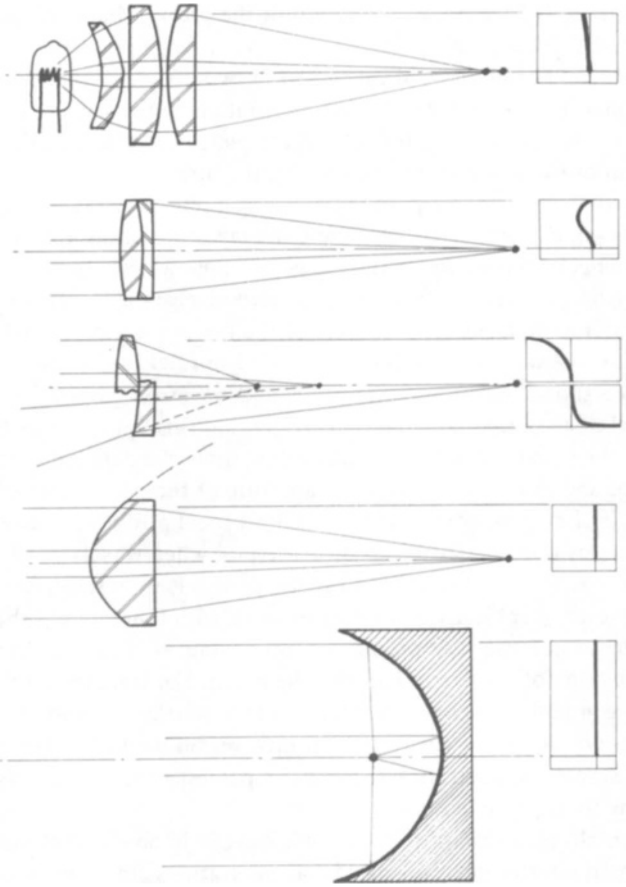


Figure 13.2 Control of spherical aberration

height; that is, a plot of longitudinal aberration. Such graphs show the fundamental nature of spherical aberration clearly enough, but optical designers are creatures of fashion and currently it is *de rigeur* to use transverse ray aberrations for design work. Transverse ray aberrations, as the name implies, are the ray intersection errors at some chosen image plane and they have some advantages for calculating and plotting oblique (off-axis) aberrations. However, they also have the disadvantage that it is not quite so easy to see the effects of changing the image plane position as is the case with longitudinal aberrations.

Ray aberrations are particularly descriptive and easy to calculate, but the physical reality of the fashion in which the 'rays' combine at the focal point indicates that light does not in fact behave in a ray-like manner in that region, owing to the effects of diffraction. For this reason, detailed aberration balancing and the calculation of precise image quality characteristics involve the consideration of the wave properties of light and the calculation of the precise shapes of the wavefronts converging on the focal points.

Wavefronts can be defined and calculated in two distinct ways: directly, as the surface of equal time delay from the object point along the rays, or indirectly as the surface that is normal to all the rays of the pencil of light. The theoretical determination of the shape of a wavefront by the direct method involves calculating the precise geometrical optical path length along a reference ray and then subtracting that from the same length calculated along the ray in question; this requires an excessive number of numerical digits or ingenious numerical methods to guarantee the necessary precision in the final result. Alternatively, the wavefront shape may be determined indirectly from the geometry of the ray intersections, taking account of the fact that the wavefront is defined as being normal to the rays.

Figure 13.3 shows the equivalence of ray and wavefront aberrations for a typical pencil of aberrated rays. The top diagram in this figure shows the physical geometry of the situation and the graphs below show the detailed variation of the three types of aberration across the semi-aperture of the optical system. The broken lines in the figure correspond to the best focal position. The selection of the best focal position is relatively straightforward when wavefront aberrations are used, but there is no reliable criterion for the same selection when ray aberrations are used; however, graphically it is easier to work with longitudinal aberrations because a change in focal position merely corresponds to a simple change in the horizontal position of the vertical axis of the graph. For transverse aberrations the corresponding graphical change is a rotation of the vertical axis about the origin, and in the case of wavefront aberrations it involves taking the horizontal difference between the wavefront aberration graph and a parabola that represents the reference sphere for the focal plane in question.

Experimentally, the situation is reversed. Wavefront aberrations may be measured directly with an interferometer, whereas ray aberrations are messy and unreliable quantities to measure.

Returning to our consideration of figure 13.2, the bottom two diagrams show how aspheric or non-spherical surfaces may be used to nullify spherical aberration completely in either refracting or reflecting systems. Both the aspheric curve on the lens and the parabolic aspheric curve on the mirror are notable for having reduced curvature as the aperture height increases, so compensating the tendency for marginal rays to focus closer to the lens than they ought to, as shown in diagram 1 of figure 13.1. This compensation has the same effect as the use of positive and negative lenses in combination, where the tendency for the positive lens to focus short at the edge of its aperture is balanced by the tendency of the negative component to focus long for the same sort of reasons, although in that case the compensation can normally be perfect only for one aperture height.

2. Longitudinal chromatic aberration

The cross-section of a lens is not unlike a prism and, just as a prism disperses light into its constituent colours, so too does a lens. Another way of perceiving the

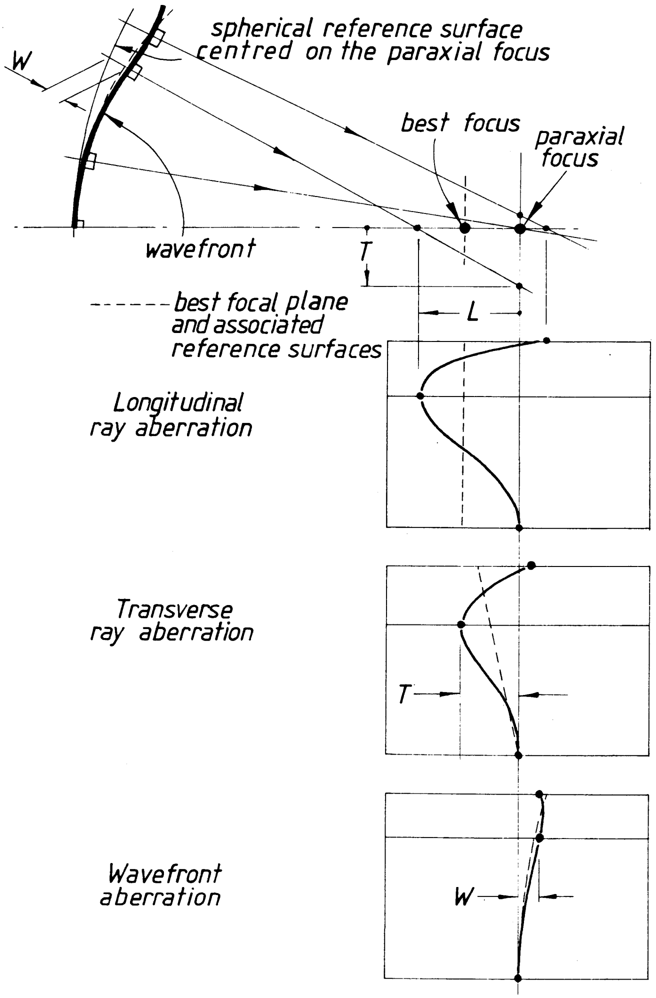

spherical reference surface
centred on the paraxial focus
W
best focus
paraxial
focus
wavefront
T
best focal plane
and associated
reference surfaces
L
Longitudinal
ray aberration
Transverse
ray aberration
T
Wavefront
aberration
W

Figure 13.3 The equivalence of ray and wavefront aberration

origin of chromatic aberration is to consider the variation of refractive index with wavelength and the consequent variation in the values of f and A′P′ etc. This chromatic dispersion manifests itself as a longitudinal displacement of the image from the nominal paraxial focus for green light, with blue focusing short and red focusing long, as shown in the diagram 2 of figure 13.1, and the first diagram of figure 12.4.

The correction of chromatic aberration has already been mentioned in the previous chapter, and figure 12.4 shows some relatively thin lens components which have been achromatised with three different degrees of refinement compared with a simple uncorrected lens.

Just as in the third-diagram of figure 13.2 the aberration of the first component of a doublet can be compensated by the aberrations of the second component, so too in the case of an achromatic combination can the chromatic dispersion of the first component be compensated by that of the second component.

In the case of spherical aberration, the contribution of an individual component depends not only on the focal power of that component but also on the distribution of focal power between its individual surfaces (its 'shape'). In the case of chromatic aberration the situation is different, the chromatic contribution of each component depends only on its focal power and the dispersion of the glass from which the component is made.

Fairly clearly, if we are to combine a positive and a negative component in contact, so that the overall power is positive, then the positive component must be more powerful than the negative component. If in such a combination the two components were made of the same glass, the chromatic aberration contribution of the positive lens component would be greater than that for the negative component and one would be left with a residual balance of chromatic aberration; but if the negative component is made from a glass that has a greater dispersive power than the glass of the positive component, then it is possible to achieve exact compensation of the two chromatic aberrations and simultaneously the required overall positive power.

Glasses with greater dispersive power are traditionally called 'flint' glasses and glasses with less dispersive power are called 'crown' glasses, so that a positive achromatic combination will consist of a positive crown lens and a negative flint lens. If a combination is required that has an overall negative power (such as the rear end of the telephoto lens shown in the second diagram of figure 12.5) then the dispersion of the positive component must be relatively greater; that is, it will be made of flint glass, while the negative component will be made of crown glass.

3. Coma

Comatic aberration arises because the edge of a lens has a different focal length to the central portion of the lens and thus the image heights corresponding to the two regions of the lens are different. This effect is illustrated in the diagram 3 of figure 13.1.

One is immediately inclined to jump to the conclusion that any lens that has spherical aberration must also have coma, because in the case of the normal type of spherical aberration the margin of a positive lens focuses the image closer to the lens than the central paraxial region does. This is not necessarily the case, and some further explanation of the meaning of focal length is necessary if we are to understand this clearly.

Previously we introduced the concept of the paraxially calculated effective focal length and made the point that this was the quantity that people were referring to when they talked about the 'focal length' of a lens. The optical engineer requires a more complete concept of focal length which may be applied quantitatively to lenses with apertures of a finite size. This is achieved by extending the concept of the principal points to the concept of principal spheres. The principal spheres are centred on the axial paraxial object and image points and they have radii of curvature equal to l and l', the paraxial object and image distances. When a lens is focused on infinity, l' of course becomes equal to the focal length and the principal image sphere has a radius equal to the focal length, whereas the object principal sphere becomes a flat surface passing through the principal point P (see figure 11.1).

In a real lens the principal sphere in the image space becomes distorted by comatic aberration so that its radius varies, and it is this radius that functions as the focal length or the image distance for the purpose of calculating image heights.

Figure 13.4 shows the anatomy of this situation, where it can be seen that for any particular ray that does not have any spherical aberration, the focal length is given by

$$\text{finite effective focal length} = -\frac{Y_0}{\sin u'} \tag{13.1}$$

where the minus sign occurs because in figure 13.4 u' is negative, whereas the focal length is positive.

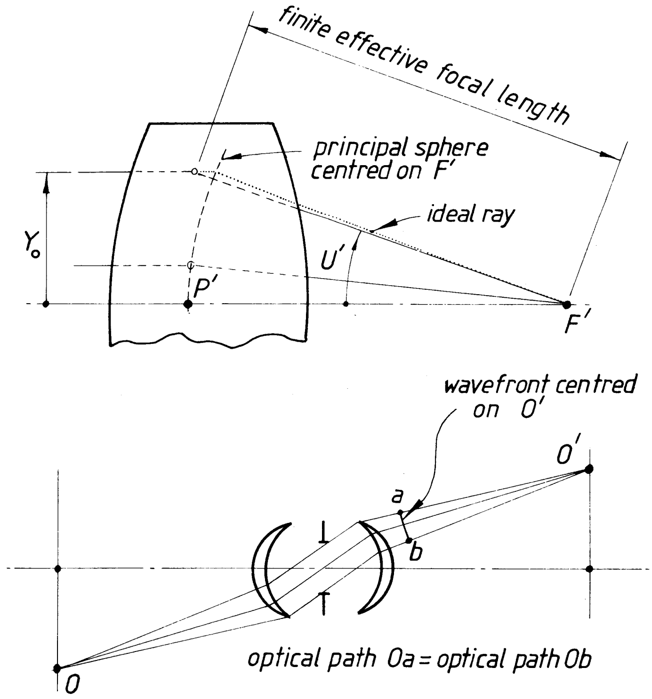

finite effective focal length
principal sphere centred on F′
ideal ray
Y₀
U′
P′
F′
wavefront centred on O′
O′
a
b
O
optical path Oa = optical path Ob

Figure 13.4 Finite effective focal length and correction of coma by symmetry

When a particular ray also has spherical aberration, it is not as easy to see which length operates as the effective focal length, but we shall be able to see that the presence of spherical aberration does not necessarily involve coma if we consider a specific example. Figure 13.5 shows a spherical mirror forming an image at its principal focus. If the aperture stop in such a situation is placed at the centre of curvature of the mirror, we can see that although the image is formed on a spherical surface (that is, there is field curvature) and that there is also spherical aberration present, there is no transverse discrepancy between the image heights formed by the margin of the aperture and those formed by the centre of the aperture; that is, there is no coma. However, if the aperture stop is placed at the mirror itself we see that the oblique image formation does involve coma and it is clear that, in the presence of spherical aberration, coma is dependent on the position of the aperture stop.

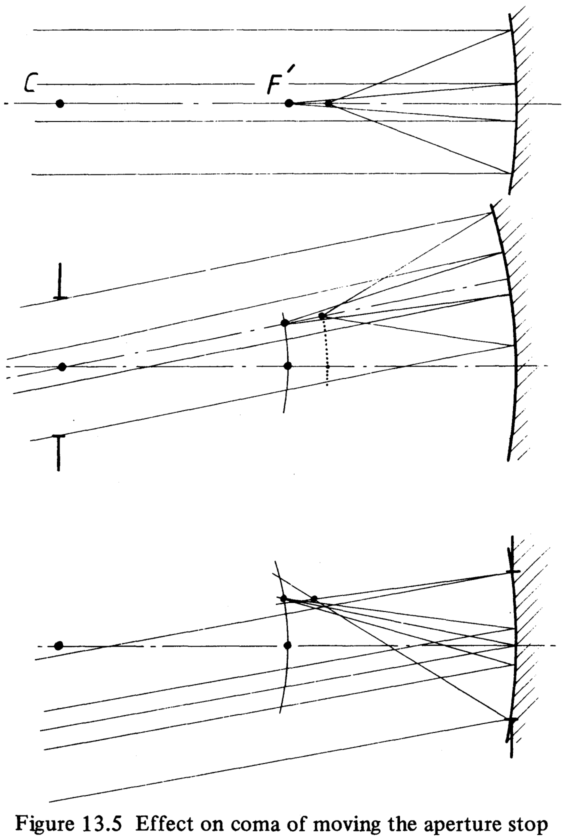


Figure 13.5 Effect on coma of moving the aperture stop

An important and much used method of correcting coma is to arrange for the shape of the optical components to be symmetrical around the aperture stop. Thus, if a positive meniscus occurs in front of the stop, with its concave surface facing the stop, the insertion of a similar component behind the stop, with its concave surface again facing the stop, enables us to control coma (and as we shall see, transverse chromatic aberration and distortion as well). Such a lens is shown in the second diagram of figure 13.4.

As we can see from the diagram 3 of figure 13.1, coma is the result of the lower rays of the oblique pencil receiving different treatment in the hands of the various refractions and reflections than the upper rays. When the symmetry about the aperture stop is observed, the upper and lower rays automatically receive symmetrical treatment, as shown in the lower diagram of figure 13.4.

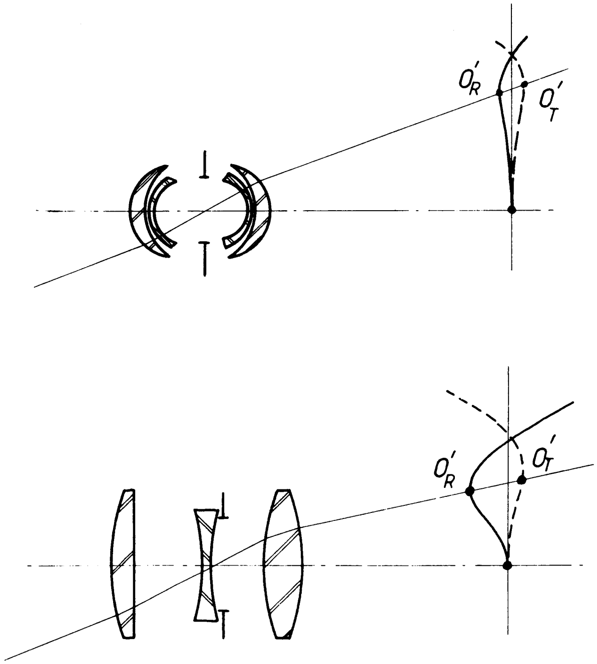


Figure 13.6 Control of astigmatism

4. Transverse chromatic aberration

From the diagram 4 of figure 13.1 it should be clear that not only does the dispersive prismatic aspect of a lens operate on the axial pencil of light but it also operates on the central or principal ray of any oblique pencil of light as well. Hence, if that ray is at a positive height on a positive lens such as is shown in the diagram, the red image height will be greater than the blue image height.

If the aperture stop is at the lens, no such chromatic dispersion takes place, and if the aperture stop is the other side of the lens then it is the blue image height that is greater, because the principal ray traverses the lens below the optical axis.

From these considerations it is relatively easy to see, for example, how the lens of figure 11.6 is corrected for transverse chromatic aberration. The central negative lens is close to the aperture stop so that the central or principal ray of each off-axis pencil of light passes through the central, non-prismatic portion of that component. The two outer positive lenses are however traversed by the principal rays below or above the optical axis, depending on which side of the stop they are situated, and thus the transverse chromatic aberration contribution of one of these lenses compensates that of the other.

If in this discussion of the lens in figure 11.6, the aperture stop is precisely at the central component and the other two components are made from the same glass and are exactly symmetrically disposed with respect to the aperture stop, there is clearly no transverse chromatic aberration; but to achieve simultaneous correction for axial longitudinal chromatic aberration the dispersions of the individual glasses have to be chosen with due regard to the focal power of the individual components.

5. Astigmatism

The effect of astigmatism is shown in the diagram 5 of figure 13.1. This is the only one of our seven primary aberrations that requires the consideration of skew rays, and for this reason the diagram is a perspective view showing how the skew rays (in what is known as the sagittal plane) focus in a different longitudinal position to the rays in the meridian plane.

At each of the two focal positions the rays in the other plane are not at their focal point, so the focus is a line rather than a point, radial in the field of view at the focus of the sagittal (skew) plane rays and tangential in the field of view at the focus of the meridian rays. The disposition of these focal lines results in the two focal positions being referred to as the radial and tangential foci.

If we imagine the optical system forming an image of a wheel which has its hub on the optical axis and its rim at the edge of the field of view, the spokes will be focused on the radial focal surface and the rim will be focused on the tangential focal surface.

In this way we see that a lens with astigmatism of this type suffers from a dual curvature of field, with one curvature for radial image structure and another curvature for tangential image structure; in this way astigmatism is intimately connected with pure field curvature, although these two aberrations are corrected in quite different fashions. Astigmatism is controlled by the angle of incidence of the principal or central ray of an oblique pencil at each of the surfaces of the optical system. If these angles of incidence can be kept small, so too can the astigmatism and this principle is widely used in optical design to control astigmatism, giving rise to constructions like those shown in figure 12.3, where the components are 'bent' to be concave to the central stop.

An alternative method of correcting astigmatism is to mix positive and negative components, which have opposite signs of astigmatism and so are able to compensate the errors of one another. This is the technique that is employed in the lens designs shown in figure 11.6 and the first diagram of figure 12.1.

Just as in the case of spherical aberration, where there is a zonal residual of aberrational error when positive and negative lenses are used to compensate aberrational contributions of one another, so too in astigmatism we find that using positive and negative lenses with large but compensating angles of incidence of the principal ray at the various surfaces in the system produces perfect compensation of the aberration at some particular field radius, but a relatively large residual error at other field radii. This is shown in figure 13.6, where the two different types of astigmatism correction are compared. The upper diagram of figure 13.6 may be compared with the spherical aberration correction shown in the first diagram of figure 13.2, and the second diagram is comparable with the second diagram of figure 13.2.

6. Field curvature

Every optical component has a natural and inevitable field curvature associated with it; thus, for example, in the case of a simple concave mirror such as that shown in figure 13.5 we can see that, if the aperture stop is closed down to a small size to remove the effects of spherical aberration and is also moved to the centre of curvature of the mirror to remove the effects of coma and astigmatism, we are left with an image that lies on a spherical surface that has its centre at the centre of curvature of the mirror. The radius of curvature of this surface is f, the focal length of the mirror, because a spherical mirror has a focal length that is half its radius of curvature.

The analogous situation for a lens is not quite so physically simple, but if we consider a thin lens that is plano convex and that has a small stop lying on the optical axis where a radius from the spherical surface is refracted to by the plane surface the astigmatism, coma and spherical aberration will be small, and the radius of curvature of the image surface will be $f \times n$. This situation is illustrated in figure 13.7, where it can be seen that the image sphere is centred on C, the centre of curvature of the refracting surface. The radius of the image surface is $f + | r_2 |$, where $| r_2 |$ is the positive value of the radius of the refracting surface, and from the expression for the focal length (equation 11.2), we have

$$r_2 = -f(n - 1)$$

As r_2 is a negative quantity, we can straight away write down the radius of the image surface as

$$\text{image surface radius} = f + | r_2 | = f + f(n - 1) f \times n \qquad (13.2)$$

The remarkable feature of this equation is that, for any thin lens of whatever shape, if a stop position can be found that removes the astigmatism, the resulting astigmatism-free image surface will be a sphere of the above radius for whatever magnification the lens is working at, assuming that the object surface is flat.

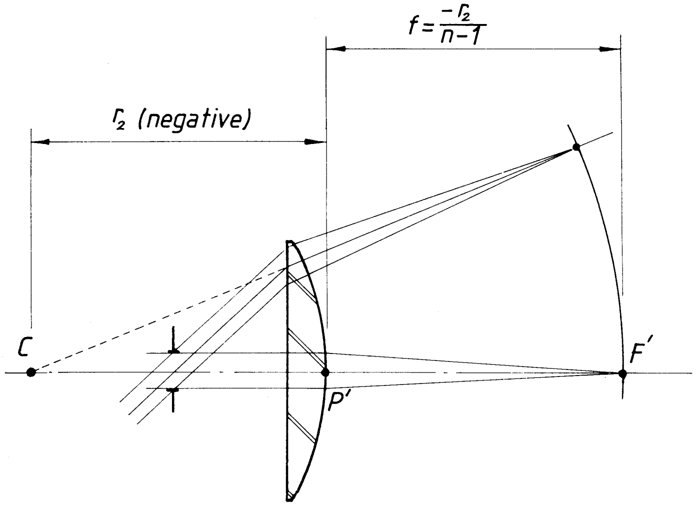


Figure 13.7 Field curvature for a thin lens

What is even more remarkable is that if the object surface is curved, an increment of curvature equal to the reciprocal of the above quantity will be added to the object curvature by the imaging step, so that we can predict the radius of the final image surface in a multi-component optical system by merely summing up the reciprocal of the quantity defined by equation 13.2 for each component of the optical system.

Any reasoning engineer may well question the assertions of the last two paragraphs and to allay suspicion we should further consider what has been said here. If we examine figure 13.8, where a diagram of an imaging step with a (transverse) magnification of M is shown, we see that the concavity (sag) of the object will be given by $h^2 \div 2r$, where h is the image height and r is its radius. The longitudinal aberration is M^2, so the concavity of the image will be $(h^2 \div 2r) \times M^2$, but this will be at an image height of $h \times M$, so the radius of the image will be

$$r' = \text{image surface radius} = \frac{h^2 M^2}{2 \times (h^2 \div 2r) \times M^2}$$

$$= r$$

which is just the same as the same quantity for the object, so the imaging does not change the radius of the relayed focal surface, except that where appropriate the intrinsic field curvature of the lens will be added to it in accordance with equation 13.2.

The remarkably simple anatomy of field curvature gives this aberration a key position in the basic layout of optical systems, and is often the first consideration in devising new optical configurations. The Austrian optical engineer Joseph Petzval was the first person to clarify this situation and the simple sum of the contributions from each of the constituent elements is frequently referred to as the Petzval sum.

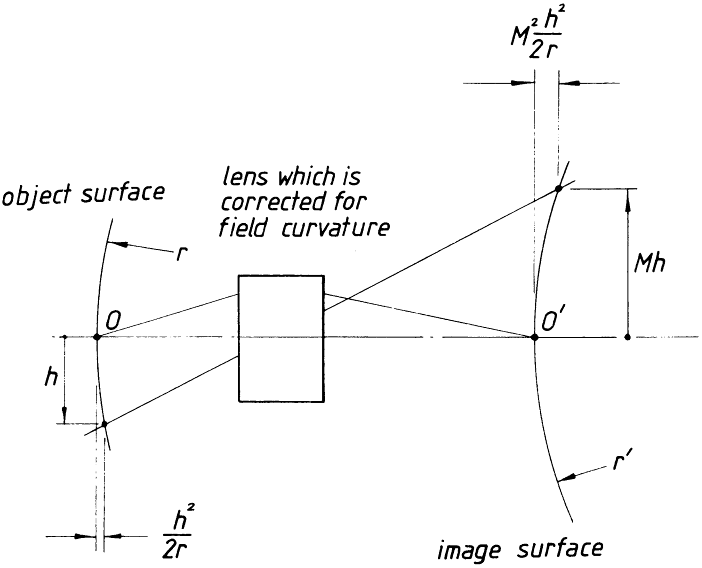

$M^2\frac{h^2}{2r}$
object surface
lens which is corrected for field curvature
r
0
0′
Mh
h
r′
$\frac{h^2}{2r}$
image surface

Figure 13.8 The invariance of field curvature

7. Distortion

An aberration that is frequently used as a misnomer for other image errors is distortion, but the optical engineer has a precise meaning attached to this error, as illustrated in diagram 7 of figure 13.1 and also in figure 13.9.

The name arises because rectangular objects become distorted when they are

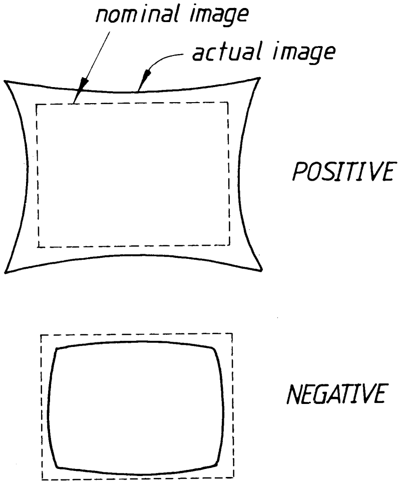

nominal image
actual image
POSITIVE
NEGATIVE

Figure 13.9 Distortion

imaged by a lens that suffers from this aberration. This distortion is illustrated in figure 13.9.

Coma, transverse chromatic aberration and distortion are all essentially transverse errors associated with oblique imagery and they may all be corrected by observing symmetry about the aperture stop, so that the lenses shown in figure 13.6 are intrinsically capable of correction for these errors, whereas eyepieces and other asymmetric optical systems are inclined to suffer from them to a greater extent.

There is a more direct analogy between distortion and coma. If in figure 13.4 the ray that is considered is the principal ray of an oblique pencil rather than a ray belonging to an axial pencil, we can see that the angle U' is not the same for the ideal ray as it is for the actual ray, and this is no more than distortion, so we may apply the analysis of figure 13.4 to the calculation of distortion if it is the principal rays that are traced rather than the axial finite rays.

14

The Design of Cemented Achromatic Doublets

In the previous chapter the correction of spherical aberration and longitudinal chromatic aberration were discussed in some detail and the reader may have noticed the similarity between the lens designs shown in the second and third diagrams of figure 13.2 and those shown in the second and third diagrams of figure 12.4. The designs shown in figure 12.4 were intended for the correction of chromatic aberration and the lens shown in figure 13.2 was intended for the correction of spherical aberration.

By the appropriate choice of refractive indices and dispersions for the two glasses that are used, both spherical and chromatic aberration may be corrected in the same doublet lens. Such a doublet is a compact and stable optical component which may be used on its own, or if its aberrations are matched to the application it may be designed as part of a more sophisticated assembly such as that shown in the first diagram of figure 12.1.

Not only may spherical aberration and chromatic aberration be corrected in such a doublet lens, but if particular care is taken in the selection of the glass types then coma may also be controlled.

When such a lens is used on its own it is capable of good imagery close to the optical axis, but because astigmatism and field curvature are not corrected it is not suitable for wide angle applications.

Because such a lens is of extensive practical application and it is relatively simple to design, we shall now go into some detail and describe the procedure for the complete design of such a lens.

At first the calculation work will seem difficult to the novice but, as the design proceeds, the tedious and difficult aspects will recede into the background and the all important aberrational information will take on a life of its own. The procedures and calculations involved in this design work are not just applicable to the design of spherically corrected achromatic doublets, and when the design is complete the novice optical designer will have mastered several useful skills and perceived the general nature of the differential design adjustment procedure.

The lens we shall choose to design will be a large diameter, long focal length lens, as might be required for a collimator or a telescope objective. We shall choose the focal length to be 1000 mm and we shall make it with a diameter of 200 mm, that is $f/5$. Such a relative aperture is not suitable for astronomical telescope applications but it might be used for some photographic purposes.

Figure 14.1 shows the final longitudinal aberrations for this design, compared on the same scale with a single plano convex lens of the same focal length and aperture.

Although mechanically the cemented doublet is very similar to the single lens, the aberrations are dramatically better and it is, of course, just this that makes the achromatic doublet such a useful optical subassembly.

To avoid a lengthy digression about the selection of optical glass for such a lens, we shall select two glasses that are known to meet the requirements of simultaneous correction for spherical aberration, chromatic aberration and coma. The requirements of these glasses to correct chromatic aberration merely means that, as the focal length is positive, the negative component should have high dispersion and the positive component should have low dispersion. Dispersion for optical glass is specified by its V value which is defined as

$$V = \frac{n_{\mathrm{d}} - 1}{n_{\mathrm{F}} - n_{\mathrm{C}}} \tag{14.1}$$

and this quantity is small for high dispersion and large for low dispersion.

We shall choose two glasses with very different dispersions: a hard crown with a V value of 60.4 and a dense flint with a V value of 36.4. The refractive indices of

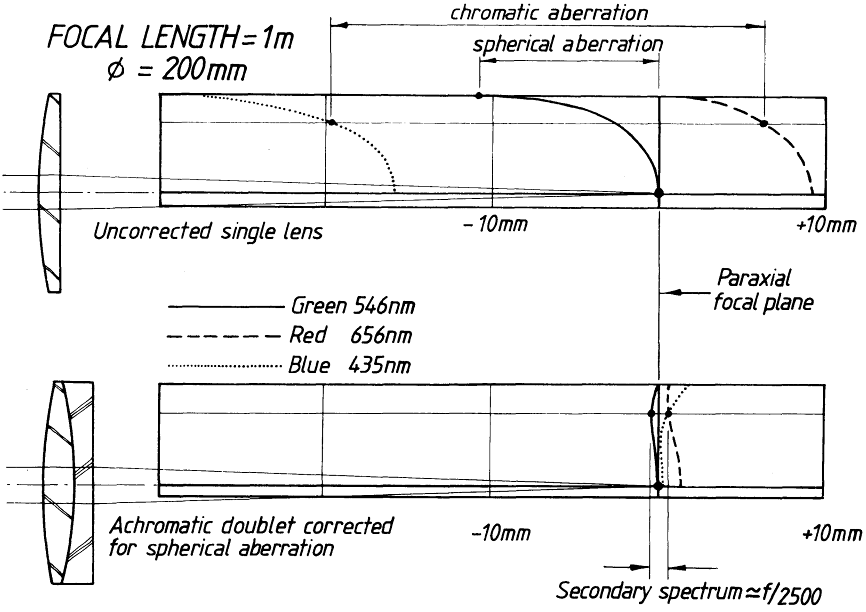

FOCAL LENGTH = 1m
ϕ = 200mm
chromatic aberration
spherical aberration
Uncorrected single lens
- 10mm
+10mm
Paraxial focal plane
——— Green 546nm
– – – Red 656nm
······ Blue 435nm
Achromatic doublet corrected for spherical aberration
-10mm
+10mm
Secondary spectrum≃f/2500

Figure 14.1 The final aberration correction compared with a single lens

these two glasses are 1.62408 and 1.52104 respectively, measured at the mercury green line, $e = 546.1$ nm, and this refractive index difference is adequate to give a negative spherical aberration contribution at the cemented contact surface, to balance the two positive contributions from the air–glass surfaces.

The correction of coma is more hit and miss. As it happens, these two glasses are a suitable choice to minimise coma, but no explicit attempt is going to be made to control coma. If the final coma correction is not suitable the lens should be redesigned with other glasses and the refractive indices selected on the basis of the changes so produced.

The wavelengths that will be used for the design will be e, C and g, which is a sufficiently wide spectrum to see a significant variation of spherical aberration correction with colour.

For clarity, we shall now itemise a detailed procedure for designing this lens. We shall choose to make the positive component more or less equi convex and the negative component more or less plano concave, and we shall also choose to cement them together (that is, we shall make the concave surface of the negative flint component the same radius of curvature as the second surface of the convex component). This configuration is arranged so that the convex component is facing the infinite object. This is not the only configuration of cemented doublet that can be designed for an infinite object and figure 14.2 shows the four most common arrangements. The selection of this particular style of achromatic doublet has the advantage that the surface curvatures are minimised.

(1) Decide on the focal length and aperture and determine over what chromatic band the lens is to be used.

(2) Select the glasses you wish to use. Usually, when the lens is to be used on its own with an infinite object (magnification = 0.0), we would select a hard crown glass or a borosilicate crown glass for the positive component and a dense flint glass for the negative component, for the reasons outlined above. If the focal length is negative then it is the negative component that will be crown and the positive component that will be flint.

(3) Write down the properties of the glasses that have been chosen; that is, the refractive indices at e, C and g wavelengths and the V values (V in this context should be calculated using e, C and g rather than d, C and F which are the more usual catalogue wavelengths).

(4) We now calculate the three curvatures required to produce achromatism, assuming that $C_3 = 0.0$. Curvature is, of course just the reciprocal of radius:

$$C = \frac{1}{R}$$

We choose $C_3 = 0.0$ to correct spherical aberration approximately. Then

$$C_2 = -\frac{V_B}{F(V_A - V_B)(n_B - 1)} \qquad (14.2)$$

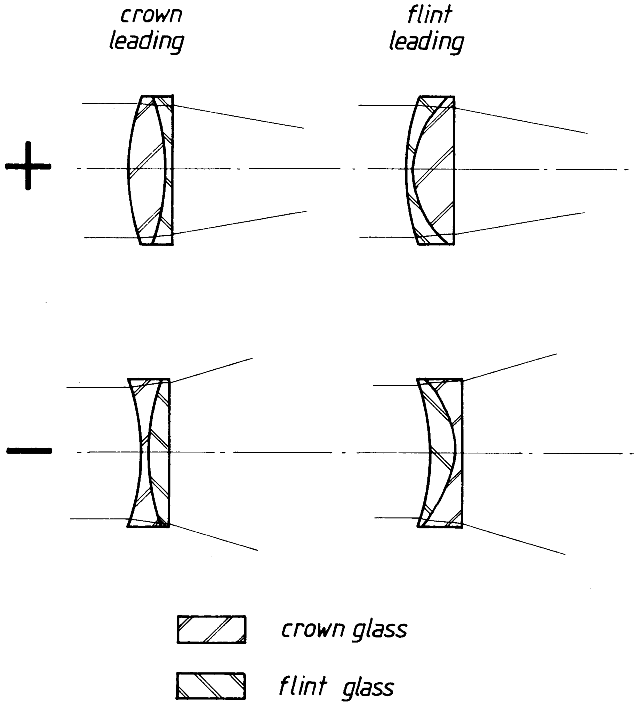


Figure 14.2 Four common configurations for an achromatic doublet

and

$$C_1 = \frac{F(V_A - V_B)(n_A - 1)}{V_A\left(1 + \frac{F(V_A - V_B)C_2(n_A - 1)}{V_A}\right)} \tag{14.3}$$

where, of course, F is the focal length of the required doublet and the subscripts A and B refer to the first and second components. Frequently the A component will be the crown glass component (whether F is positive or negative) in order to minimise the surface curvatures.

(5) Having calculated these starting curvatures, we next choose centre thicknesses for the components. Generally for average focal lengths, the thickness of the negative component can be the diameter ÷ 10, while the thickness of the positive component can be

$$t_{+\text{ve}} = \frac{D}{30} + \frac{D^2}{8}(\,|C_1| + |C_2|\,) \tag{14.4}$$

where D is the diameter of the doublet and $|C_1|$ is the absolute value of C_1 (that is, the positive value) and $|C_2|$ is the absolute value of C_2. This gives adequate edge thickness.

(6) Now comes the difficult bit – raytracing! There is no avoiding this, it *is* tedious but once mastered is just a matter of routine. Personally I feel that these days there is no reason to flog through these calculations with a simple calculator. For really very little money one can purchase a simple programmable calculator which can handle a cemented doublet as one integrated raytrace calculation.

With an eye to doing this calculation on a calculator we will use one set of equations to trace both paraxial rays and meridian finite rays. If a computer were being used we would choose to have a separate program segment to deal with each type of ray (paraxial, meridian finite and skew), and even if we were using an unprogrammable calculator we would probably choose to trace paraxial rays to locate the focal point at each step.

Figures 14.3 and 14.4 show the geometry of tracing a finite meridian ray through our doublet. The starting data for the ray is U, the ray angle, and a, the perpendicular distance from the ray to the pole of the surface in question.

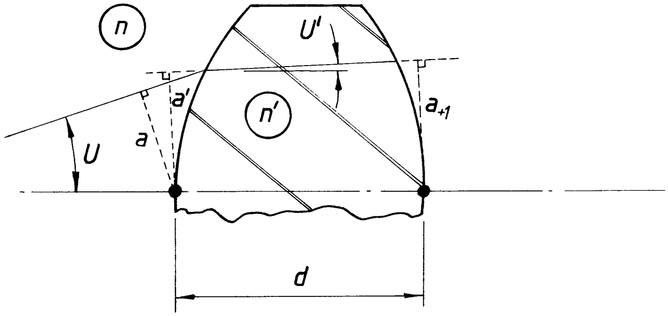


Figure 14.3 Finite raytracing

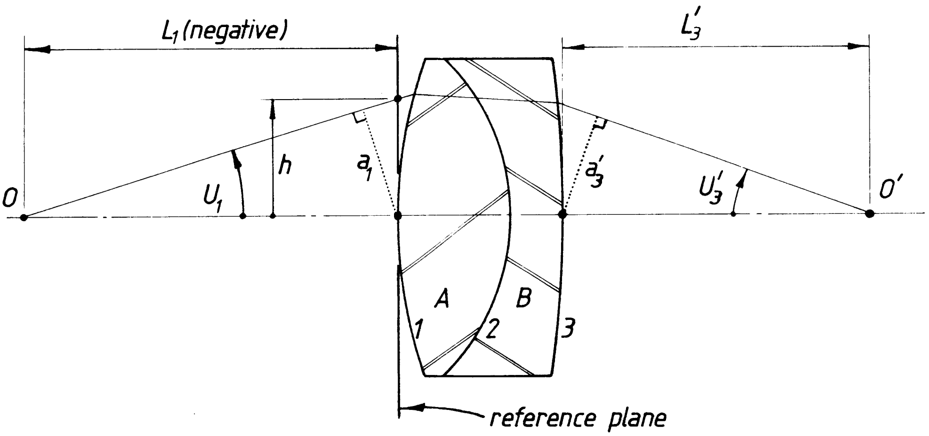


Figure 14.4 'Opening' and 'closing' a finite raytrace

Then, the ray angle after refraction is given by

$$\boxed{U' = \sin^{-1}\left(\frac{n}{n'}(aC + \sin U)\right) + U - \sin^{-1}(aC + \sin U)} \tag{14.5}$$

and the perpendicular to the ray after refraction is given by

$$\boxed{a' = a\,\frac{\cos U' + \cos \sin^{-1}\left(\frac{n}{n'}(aC + \sin U)\right)}{\cos U + \cos \sin^{-1}(aC + \sin U)}} \tag{14.6}$$

These are the refraction formulas and together they perform the same function as equation 11.8 does for paraxial rays.

The transfer to the next surface is calculated with a formula which is analogous to equation 11.11

$$\boxed{a_{+1} = a' + d \sin U'} \tag{14.7}$$

At the start of each raytrace it is necessary to calculate the opening values for a_1 and U_1, and figure 14.4 shows the geometry that applies in this situation

$$U_1 = \tan^{-1}\left(\frac{h}{-L_1}\right) \tag{14.8}$$

$$a_1 = -L_1 \sin U_1 \tag{14.9}$$

Equations 14.8 and 14.9 apply to the situation where the object is at some finite distance from the first surface, but when L_1 = infinity we have to apply equations 14.10 and 14.11

$$U_1 = 0.0 \tag{14.10}$$

$$a_1 = h \tag{14.11}$$

At the end of the raytrace we need to calculate the longitudinal intersection distance L'_3, which is given by equation 14.12

$$L'_3 = \frac{a'_3}{\sin(-U'_3)} \tag{14.12}$$

(7) Tracing a single ray tells us very little and we need to trace at least four rays to determine the state of correction of the doublet. These four rays are shown in figure 14.5.

The novice might well ask at this stage: how does one trace rays in different colours? This is achieved by using the appropriate refractive indices for the glasses.

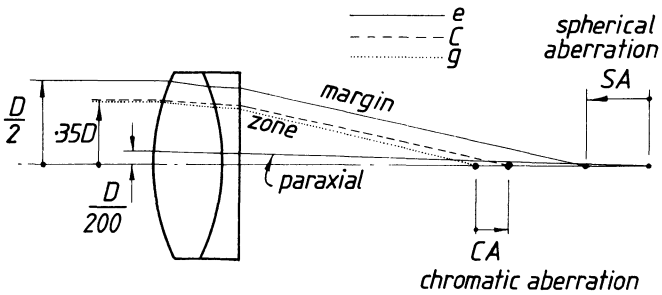


Figure 14.5 The four rays required for aberration calculation

For simplicity we shall define the two aberrations we are interested in in the following way

$$\text{spherical aberration} = \text{SA} = (L'_{3,\text{margin}} - L'_{3,\text{paraxial}})_e \tag{14.13}$$

and

$$\text{chromatic aberration} = \text{CA} = (L'_{3,\text{zone}})_C - (L'_{3,\text{zone}})_g \tag{14.14}$$

Thus, to calculate the spherical aberration we have to trace the marginal and paraxial rays in *e* light, and to calculate the chromatic aberration we have to trace the zonal rays in *C* and *g* light. *Each* ray traced involves using the refraction and transfer equations at each of the three surfaces, and the 'opening' and 'closing' formulas of section (6) to start the ray and calculate L'_3 each time. So do not underestimate the work involved!

(8) Having calculated the SA and the CA we have to change the doublet system systematically until both aberrations are zero.

Changing C_2 on its own alters the CA and changing C_1, C_2 and C_3 together, all by the same amount, alters SA ('bending').

These changes are not absolutely pure (or 'orthogonal' as mathematicians would say) but they are sufficiently independent to work well enough for practical purposes.

By making a small change of either C_2 or C_1, C_2 and C_3 together, we can investigate the variation of CA or SA with each of these two types of change. Having done this we can scale up the small changes we have made to achieve the required value of the CA or SA, whichever it is we are working on.

As we quickly discover, a simple scaling of the small change we initially make does not bring us directly to the required value of aberration (usually zero), owing to the non-linear behaviour of the aberration as the curvatures are changed. The result is that we make a series of changes which gradually improves the aberration that is being controlled. When that cycle is completed it is then necessary to do the same thing to the other aberration and so on, until both aberrations are within acceptable limits.

A natural tolerance on longitudinal aberrations emerges from a consideration of the secondary spectrum, which is illustrated in figure 12.4. The longitudinal separation between the green focus and the red + blue focus is approximately $f \div 2500$ (see also figure 14.1) and we clearly do not need to control SA or CA to better than some arbitrary small fraction of this quantity, say one-twentieth of it.

(9) The systematic adjustment of the curvatures to control CA and SA is representative of the central technique of lens design, not just for these aberrations and in the context of an achromatic doublet, but for any aberration in any context, so it is worth considering the method in some detail.

In figure 14.6, A_0 represents the starting value of the aberration, while A_1 represents the value of the aberration after a small arbitrary change. Then, using the values of A_0 and A_1 we can predict a value of the constructional parameter(s) (curvature(s) in our case) that gives a value of A_2 to the aberration. We then use A_2 and A_1 and interpolate to find the value of the constructional parameter(s) that gives A_3 and so on, until A_n is small enough.

This is the well-known chord version of the Newton–Raphson differential correction procedure.

For rapid and convenient use of this method we usually remember a formula

$$\Delta \mathrm{CP} = -\frac{A_c}{\mathrm{Diff}}$$

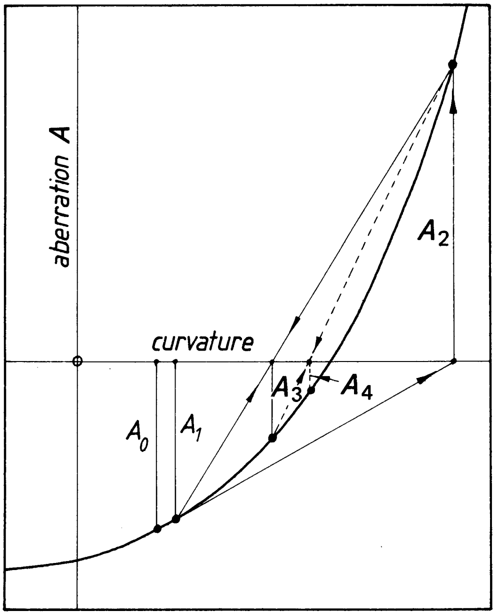


Figure 14.6 Differential correction

where ΔCP is the required change in the constructional parameter(s), A_c is the current value of the aberration, and Diff is the differential coefficient of the aberration curve. This last quantity is defined as the ratio of the change of aberration to the change of constructional parameter, that is

$$\text{Diff} = \frac{\Delta A}{\Delta \text{CP}}$$

This does not have to be computed particularly precisely and in the above calculation it was approximated by the slope of the chord between any two successive points on the aberration curve. One can often not bother even to recompute it after the first round of prediction, although that is not to be generally recommended.

(10) We must now consider coma. When we set up the initial solution to our doublet we chose $C_3 = 0.0$, which was to correct SA approximately, and then went on to improve the SA situation to the point where it was zero at the margin of the lens.

For coma we chose glass types in the HC or BSC and DF or EDF regions to reduce the effect; however, we then did not go on to improve or even calculate coma. For completeness, it is now necessary to compute the coma of our completed lens and decide whether we need to try and improve it. The only way we could do this is to change one or both of the glasses, and redesign the lens from scratch. Although it would also be possible to 'break' the contact (that is, to make the curvature of the back of the crown lens different to that of the first surface of the flint component) the difficulties encountered in that sort of design, though not difficult to comprehend, are sufficiently awkward to put it beyond the reach of the beginner.

The calculation of coma for our completed lens is simple. We calculate the marginal and axial focal lengths of the doublet (assuming it is a lens that works at infinity) by using the relationship shown in figure 13.4, and then calculate the corresponding image heights at the edge of the intended field of view and decide if the transverse image spread is acceptable, in terms of the specification that the completed lens is intended to work to.

For lenses working at finite conjugates, the calculation of coma is a little more subtle. In this situation, magnification takes over the role that focal length fulfilled in the discussion of coma for when the object is at infinity.

The magnification at which a lens works is given by the equation

$$M = \frac{\text{image distance}}{\text{object distance}}$$

This equation for calculating magnification is the 'schoolboy' method, but for the purpose of calculating coma the distances have to be interpreted in the same way as focal length has been (that is, as finite slope lengths along rays) and figure 14.7 shows how this is done.

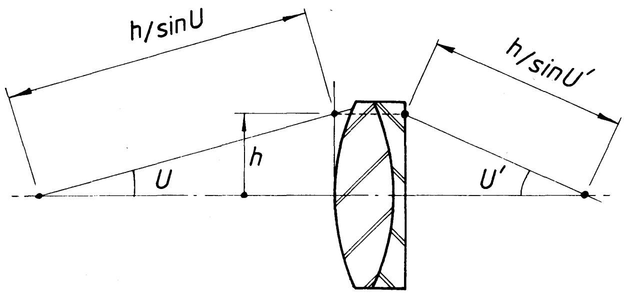


Figure 14.7 Marginal magnification

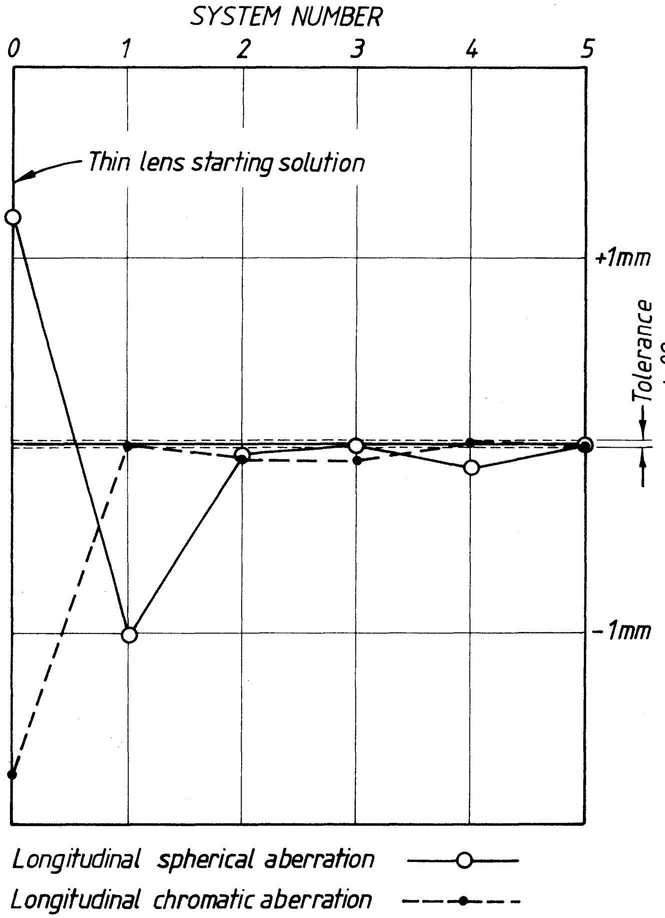


Figure 14.8 The progress of aberration correction during the differential adjustment of an achromatic doublet

From figure 14.7 we can now calculate the magnification from the equation

$$M = \frac{h}{\sin U'} \div \frac{h}{\sin U} = \frac{\sin U}{\sin U'}$$

So, by tracing a ray from the object point in the usual way, at the centre of the aperture and at the edge of the aperture, we arrive at two values of the magnification, which should, of course, be the same, but which are not exactly the same unless the coma is corrected.

Conclusions

Assuming the coma of our doublet is acceptable, it is interesting to look back at the efficiency of our improvement process. Figure 14.8 shows how the two aberrations we controlled converged on the required zero values.

The initial prescription of the lens we designed was as follows

$C_1 = 0.002398$

$C_2 = -0.002423$

$C_3 = 0.0$

$t_A = 26.47$ mm, glass = HC519604

$t_B = 20.30$ mm, glass = DF620364

$f = 994.5987$ mm

CA = −1.73553 mm

SA = 1.21826 mm

The final prescription was as follows

$C_1 = 0.002346$

$C_2 = -0.002347$

$C_3 = -0.000053$

$t_A = 26.47$ mm, glass = HC519604

$t_B = 20.30$ mm, glass = DF620364

$f = 982.9370$ mm

CA = −0.00798 mm

SA = −0.00611 mm

Marginal focal length = 976.4417

15

Interferometers and Their Applications in Optical Testing

No optical engineer can do without some knowledge of interferometry. Interferometers are used in all sorts of testing and measuring situations and interferometry is the basis of those exciting and ubiquitous subjects holography and diffraction.

The experimental manifestations of interferometry are often visually dazzling, and give the observer a brilliant insight into the nature of light and the mechanisms of image formation. The applications of interference are also of vital importance to both practical instrument makers and, at the other end of the esoteric scale, holographers, theoretical cosmologists and those interested in relativity.

The purpose of this chapter is to explain from first principles how two beam interferometers work, and then to describe some important practical interferometers used for testing optical components and systems.

The experimental facts and a fundamental example

There are many classes of interferometers, but the most important and widely used class is the two beam types, which, as the name suggests, have two beams of light. These two beams of light are always formed by some beam divider acting on a single source of light, so that the electromagnetic vibrations in the two beams are synchronous or 'coherent'.

We shall now consider a very simple, educational and inexpensive interferometer made from a piece of aluminium foil with two pin holes in it, which operates as a beam divider: one beam passing through one pin hole and the other beam passing through the other pin hole. The light source can conveniently be a distant street lamp, or any small source, and the two beams can be made to recombine and interfere with our own eye. This interferometer does not exhibit any of the traditional disadvantages associated with interferometry: high cost, twitchy mechanical adjustments or special light sources, but it gives excellent, high contrast, stable interference fringes, and it is particularly relevant if we are to understand two beam interferometers.

The interferometer is shown in figure 15.1, and it is instructive to consider a number of features of the fringe formation. First of all, notice that there is an ambiguity about what the observer sees: is it an image of the street lamp, or is it an interferogram? The answer is that it is both, but, because the pin holes are very much smaller than the eye pupil, the image features are not very clear. This touches on information theory and diffraction: the image is not clear because it is difficult to squeeze a lot of information through two small pin holes or, to put it another way, diffraction at the pin-hole apertures has blurred the information. Diffraction is the bending of light by electromagnetic disturbances close to the edge of apertures and the subsequent interaction between the deviated light rays. In the case of our pin holes there is more 'edge' than 'hole', so to speak, so it is hardly surprising that there is no clear image of the lamp. The smaller the pin holes, the larger the blurred patch is.

Secondly, consider the pattern as an interferogram. Because there are two beams overlapping on the retina, and because these two beams are coherent or synchronous in their electromagnetic vibrations (having both originated from the same source) then we see dark bands crossing the 'image', dark bands that are perpendicular to the direction of separation of the two pin holes. We call these dark bands interference 'fringes', and the whole pattern an 'interferogram'. The further apart

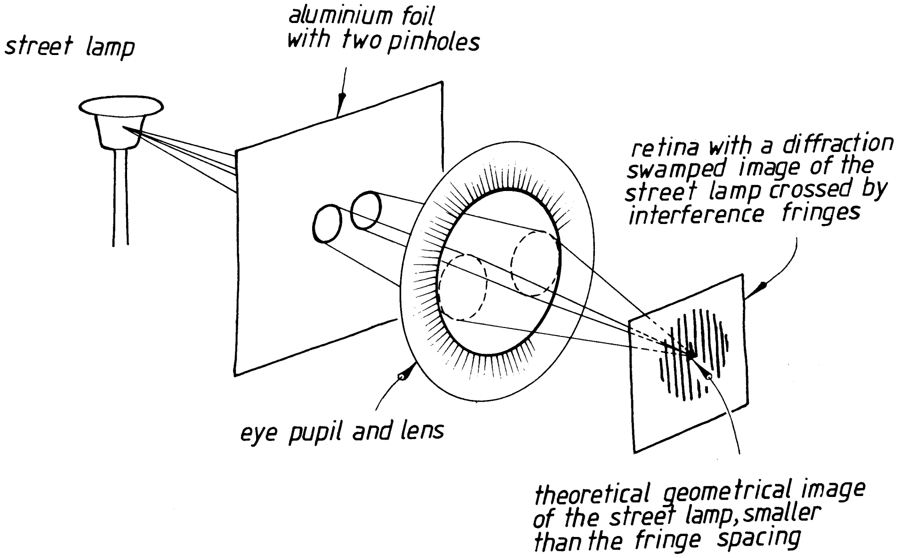

street lamp
aluminium foil with two pinholes
retina with a diffraction swamped image of the street lamp crossed by interference fringes
eye pupil and lens
theoretical geometrical image of the street lamp, smaller than the fringe spacing

Figure 15.1 A basic two beam interferometer

the pin holes are, the closer together are the fringes; because the angle of inclination of the two interfering beams at the retina increases as the pin holes are moved apart.

So we can (and I recommend that you do!) experiment with different sized pin holes and different pin-hole spacings and observe the effects on the image-interferogram.

The educational aspects of this interferometer do not stop here. Consider now the effect of the source that is used. Each point on the street lamp will give rise to a set of interference fringes on the retina and, if the geometrical image size on the retina is large, then the many fringe patterns formed by the different parts of the lamp will overlap and reduce the contrast of the interference fringes that are seen. Thus, the contrast of the fringes tells us about the angular size of the image of the street lamp as seen from the observer's position. This is just the same as the Michelson stellar interferometer which is used to measure stellar diameters by moving the pin holes apart until the fringe contrast drops to zero. Michelson used a telescope instead of the eye and his 'pin holes' were mirrors separated by many metres on a beam mounted on the front of a telescope (see figure 15.2).

Even this does not exhaust the educational aspects of this elegant instrument. If instead of a single lamp, the source had consisted of a series of slits perpendicular to the line of separation of the pin holes, and at such a distance that their retinal images had the same spacing as the fringes, then the separate fringe patterns formed by each source slit would all reinforce each other and one would not know whether one was looking at an image of the slits or an interferogram formed by a single source slit. If however the slits were at some other spacing, there would be confusion in the retinal plane and no recognisable image formed. Thus we can think of our interferometer as a filter, a spatial filter, tuned to a particular object; that is, it can only form a recognisable image of a particular row of slits arranged to be perpendicular to the direction of separation of the pin holes.

And we have not finished yet! If the retina was replaced by a photographic plate and the fringe pattern was recorded, developed, and replaced in position, then we

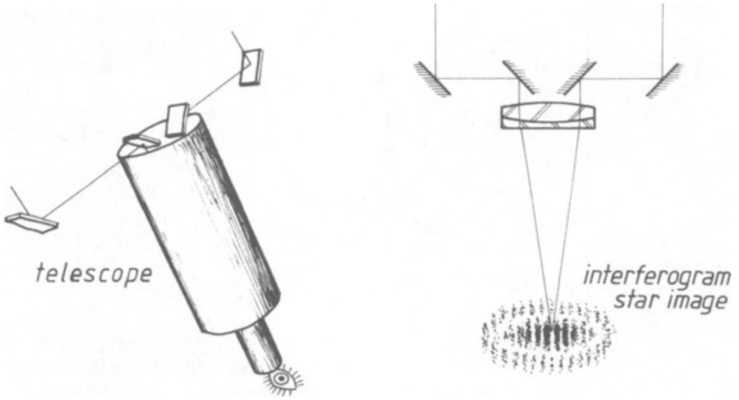


Figure 15.2 Michelson's stellar interferometer

could use it as a hologram! Its holographic aspect emerges if we illuminate one of the pin holes again, because then an image of the other pin hole would be reconstructed just where it was before. Of course, if we reconstructed with white light, not just a single reconstruction would appear, but a whole chromatic spectrum of reconstructions – so not only is our interferogram a hologram, but it is also a diffraction grating that could be used as a spectrograph, and it is, of course, also a rather poor image of the original street lamp!

So in one simple, inexpensive experiment we have demonstrated interference, diffraction, tuned spatial filtering, holography, spectroscopy and stellar interferometry!

As much fun as all that may be, it is really only the interferometric aspects of the double aperture that we want to consider further.

Two beam interferometry

So far we have been very glib about the details of how the actual interference takes place. All that has been said is that if you allow two coherent beams of light to mix they will interfere to produce interference fringes – an interferogram – but we now need to look at this in a bit more detail. Figure 15.3 shows the situation that exists at the retina in the case of our double pin-hole interferometer. Careful consideration of the rather complicated diagram showing the intersecting wavefronts leads to an equation for the spacing of the fringes

$$\text{fringe spacing} = \frac{\lambda}{2\sin\left(\dfrac{\theta}{2}\right)}$$

where λ is the wavelength of the light.

If the angle θ is small and expressed in radians (1 radian = 180 degrees/π = 57.2958 degrees) then we can write

$$\text{fringe spacing} = \frac{\lambda}{\theta}$$

This is because in radian measure, for small angles

$$\sin\theta \doteq \theta$$

This fringe spacing equation applies to all two beam interferometers and, although we could now put some numbers into it and get fringe spacing on the retina, and then work out whether the retina can resolve them or not and so on, we shall instead move on and consider some more versatile interferometers.

All the interferometers we are going to discuss are of the two beam type, and they will all pass two beams of coherent light into the observer's eye, usually along with some image information as well. In this respect the instruments we are going

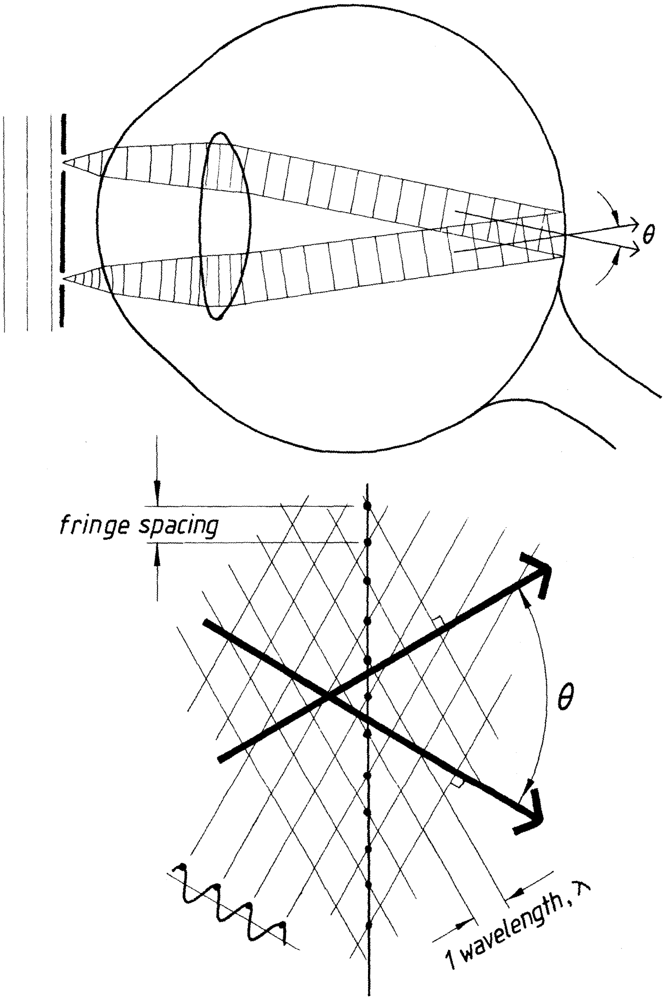


Figure 15.3 Fringe formation

to consider will be superior to our double pin-hole interferometer which, after all, did not produce a very recognisable image of the street lamp!

Another feature of the interferometers we are going to consider will be that they will provide adjustment for the inclination of the two interfering beams (the angle θ in figure 15.3), and they will also allow objects for measurement or comparison to be placed in one or both beams, so that the beams are often well separated for reasons of operational convenience.

Whereas the interferometer that we have considered so far had two very small separate coherent sources at the pupil of the observer's eye, most of the interferometers we will now consider will have two rather larger coherent sources which will usually overlap and which may be adjusted in relative position to give straight line fringes (or no fringes at all when they are exactly coincident). These coherent sources will always be two images of the same source, and they will usually be the same way up and of the same size, so that all pairs of points on the two images will produce the same fringe pattern on the retina. In the jargon of interferometry, there will be a high degree of spatial coherence between the two sources.

Finally, before we discuss specific interferometers, we will consider a theoretical general interferometer so that we may establish some names for key components and features. Such an interferometer is shown in figure 15.4. Part (a) of this figure shows how the two coherent source images are formed by a collimating lens and a decollimating lens; these images are formed on the pupil of the observer's eye and we can call them S_1' and S_2'. Part (b) of the figure shows how some plane O in the interferometer is imaged out on to the retina of the observer's eye, so that it is in focus; it is the plane O that the observer is viewing and, because the source images S_1' and S_2' are of finite size, it is only the plane O that is in focus.

So we see that there are two more or less independent systems of image formation: the source or aperture imagery and the object or observation imagery; this is true of nearly all optical instruments and not just interferometers, although the distinction is particularly clear in the case of the interferometer.

Specific interferometers

In each of the following interferometers the setting up procedure involves superimposing the two source images in both longitudinal and transverse position. The longitudinal superimposition is achieved by focusing the optical system under test, and the transverse superimposition is achieved by tilting the reference mirror or the optical system. An additional adjustment that is necessary is to equalise the length of the reference and test paths. When all three adjustments have been made, fringes will be seen.

The Fizeau interferometer

This interferometer is shown in figure 15.5. The two source images are formed by reflections from two surfaces that are nearly in contact. If the two surfaces are of the same shape, the wavefronts reflected from them will be of the same shape and the interference fringes seen on the contact surface by the observer will be straight. If the two surfaces are not only the same shape but also parallel, then the fringes will be widely spaced and the field of view either black or white. Notice that the collimating and decollimating lenses are one and the same lens in this interferometer. The eye, of course, is placed at S_1', S_2', and S is an aperture illuminated with a suitable light source.

In this interferometer the collimating cum decollimating lens is placed close to

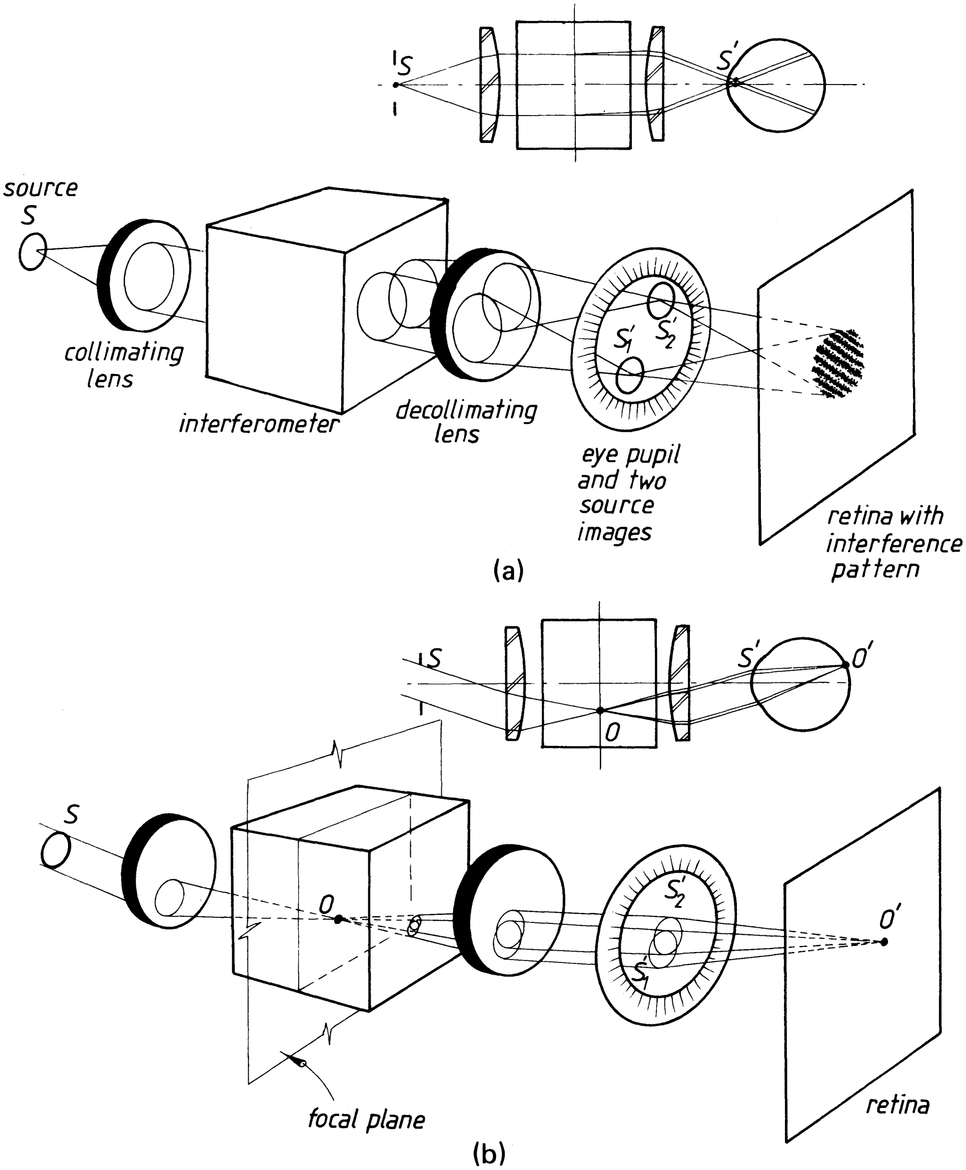

S
S′
source
S
S_1'
S_2'
collimating lens
interferometer
decollimating lens
eye pupil and two source images
retina with interference pattern
(a)
S
S′
O′
O
S
O
S_2'
S_1'
O′
focal plane
retina
(b)

Figure 15.4 A general two beam interferometer showing (a) the source imagery, (b) the object imagery

the interferometer (the two plates) and performs the function more of a field lens than of a true viewing lens such as is illustrated in figure 15.4, part b, and the observer has to use the accommodation of his eye to focus on the plates which are only just the other side of the lens.

This interferometer is found in this form in most glass workshops, and it is also

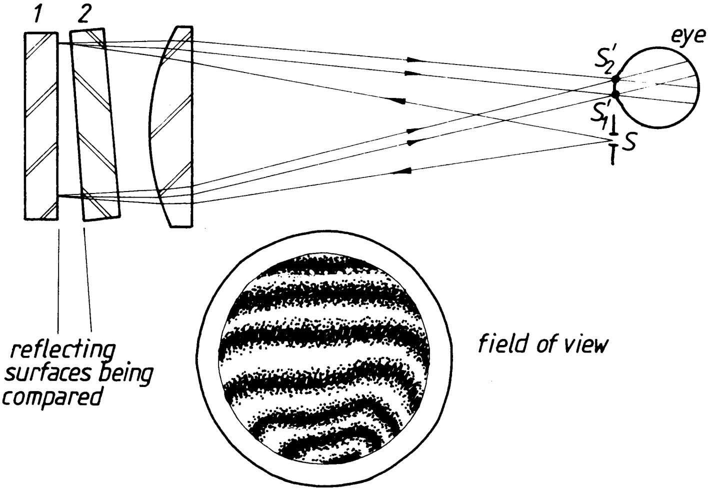


Figure 15.5 The Fizeau interferometer

found even more universally in a cruder form as the common test plate that the glass worker uses to check optical surfaces as they are polished. In this latter form the collimating field lens is dispensed with and a large source is used to make fringes visible over as much of the surface as possible.

One may well ask: where have these wavy fringes come from in the picture of the field of view? They are obviously important because they look as though they tell us about the shape of the surface being tested, but how are they formed?

So far we have discussed only interferometers that appear to produce straight fringes but, of course, the whole idea of interferometers for testing is that they show us surface shapes. What happens is that one of the wavefronts shown in figure 15.3 will not necessarily be flat but, rather, distorted by reflection or refraction from an unflat surface. So the fringe positions shown in figure 15.3 are no longer regular and evenly spaced, and the pattern on the retina no longer consists of straight parallel fringes, but is now the sort of pattern seen in figure 15.5 or figure 15.6.

As far as the user of any interferometer is concerned, the shape of these fringes can be interpreted as shown in figure 15.6, which shows a distorted test wavefront intersecting a set of tilted reference wavefronts. The tilt comes from the separation of S_1' and S_2', and the distorted wavefront shape comes from the optical component(s) under test. Although figure 15.6 looks remarkably ferocious, anybody with any technical drawing experience should be able to interpret it fairly easily. Probably because drawings like figure 15.6 do look so ferocious, the interpretation of fringe patterns is the subject of a lot of attention from computer techniques these days, and at the press of a button (or two) the mathematical shape of any wavefront can be derived from digitised versions of the interferogram.

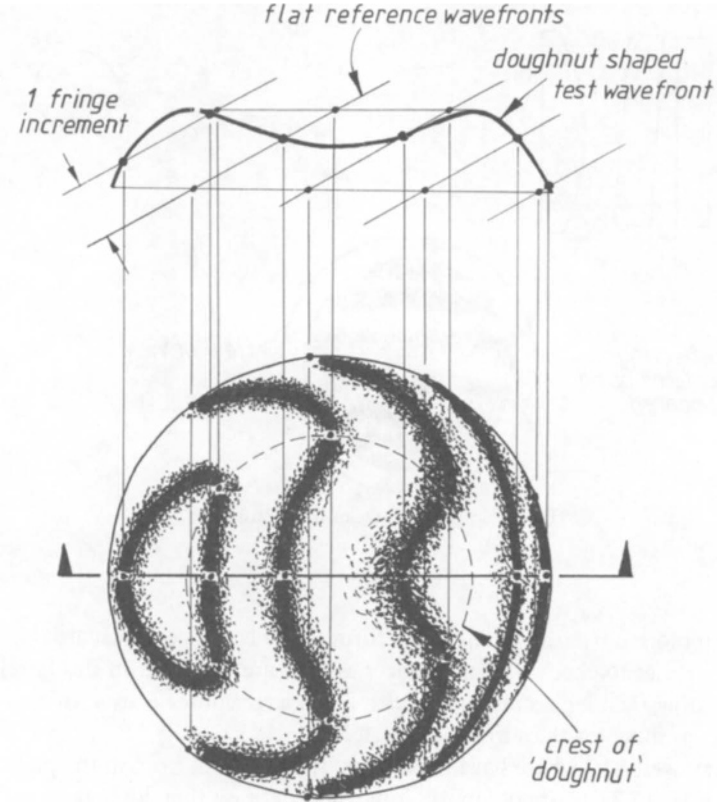


Figure 15.6 Fringe shape interpretation

The Michelson–Twyman-Green interferometers

The Twyman-Green interferometer is the classic form of the two beam interferometer and is directly derived from the Michelson interferometer by the addition of the collimating and decollimating lenses that we have already described as part of the general two beam interferometer.

The Michelson interferometer is shown in figure 15.7, part (a), and is not to be confused with the Michelson stellar interferometer which was mentioned earlier and shown in figure 15.2.

The Twyman-Green interferometer is shown in figure 15.7, part (b).

For the practical optical instrument maker it is hard to overemphasise the importance of the Twyman-Green interferometer; its most obvious application would seem to be the testing of flat mirrors, because it is only necessary to replace M_1 or M_2 by the mirror under test to get a direct, non-contact comparison between the two mirrors in the instrument. However, because the instruments own mirrors are normally fully aluminised, the instrument is not often used for testing reflective plain glass surfaces, and in any case the inexpensive Fizeau interferometer

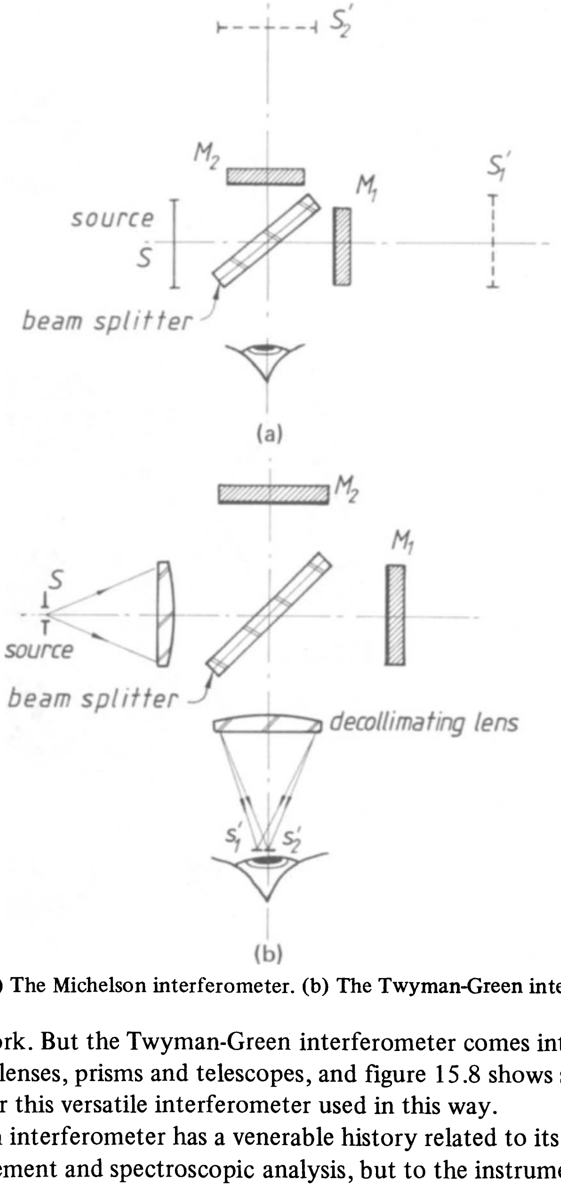


Figure 15.7 (a) The Michelson interferometer. (b) The Twyman-Green interferometer

exists for that work. But the Twyman-Green interferometer comes into its own for testing complete lenses, prisms and telescopes, and figure 15.8 shows several configurations for this versatile interferometer used in this way.

The Michelson interferometer has a venerable history related to its applications in length measurement and spectroscopic analysis, but to the instrument maker it is of less interest than the Twyman-Green interferometer, and for the purpose of this account it does not form source images at the pupil of the observer's eye in the normal way; so we shall scurry past it content that we have at least mentioned it!

The tilt between the two beams of light entering the observer's eye in the Twyman-Green interferometer is produced by tilting one or other of the mirrors to produce straight fringes, rather than the null fringes that arise if S_1' is exactly superimposed on S_2'. The first application for this instrument, illustrated in figure

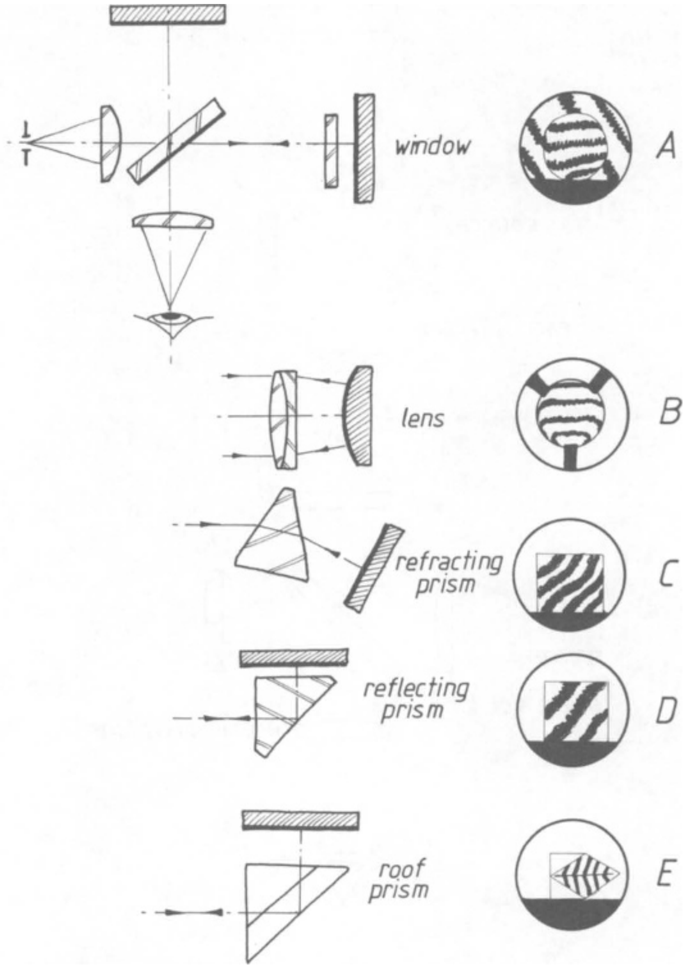
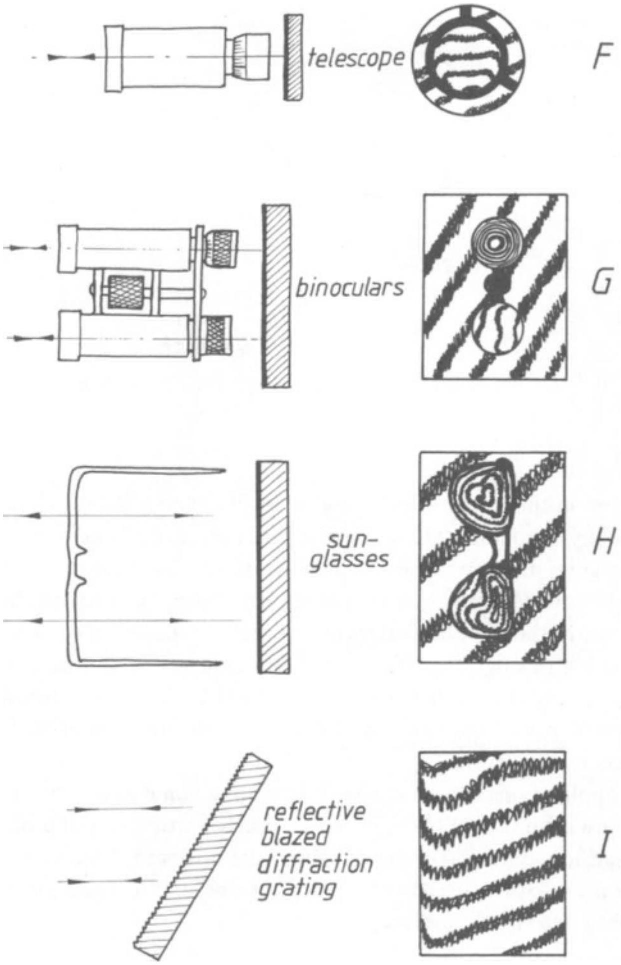


Figure 15.8 (above and opposite) Twyman-Green test configuration

15.8, amply demonstrates the power of such fringes of tilt. The interferogram shown in diagram A of figure 15.8 consists of background fringes which should be perfectly straight, formed by light that passes outside the aperture of the window under test, and also fringes formed by light that has passed twice through the window under test. The latter fringes show all the errors of the window: surface flatness, glass inhomogeneity and the magnitude and direction of the wedge in the window. Figure 15.9 shows the source images at the pupil of the observer's eye which correspond to diagram A of figure 15.8; notice that the direction of the relative displacement of the source images is perpendicular to the fringes that are formed.

The wealth of information contained in the interferogram of diagram A of figure 15.8 can be an embarrassment if we do not know something more about the



window under test. Are the irregular fringes due to glass inhomogeneity or surface shape? This dilemma can be resolved by additionally examining the window with a Fizeau interferometer to determine the surface shapes directly.

Notice that the only interferograms in figure 15.8 that have background fringes are the window, telescope, binocular and spectacle examples, this is because it is only in these examples that the direction of the light is undeviated and the plane background mirror remains untilted and not replaced by a spherical mirror. For the window, the background fringes act as a reference to measure the wedge of the window. For the telescope, the background fringes confirm that the telescope is working axially, while for the binoculars and spectacles, they are a reference for calculating deviations in the line of sight produced by the instrument.

In the case of diagram G of figure 15.8, we have taken artist's licence, and drawn

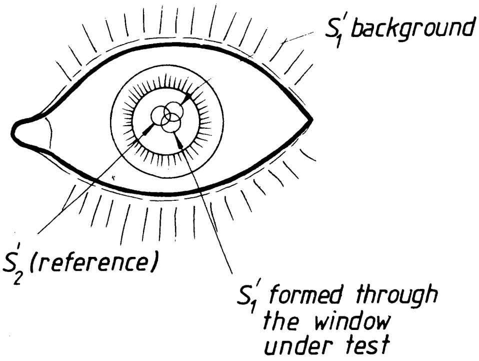


Figure 15.9 The illumination of the observer's eye, corresponding to diagram A of figure 15.8

the interferogram in the upper telescope as it would appear if the telescope were out of focus. Many binoculars allow the separate focusing of one of the telescopes, so this interferogram might well be what one would see on first offering-up the binoculars to the interferometer. A simple adjustment of the independent eyepiece focus would remove the circular fringes and reveal the direction of 'wedge' of the line of sight passing through that half of the binoculars. I should perhaps add that no-one would actually test binoculars like this, as elegant as the method may be, because you would need a very large and expensive interferometer to do it, and it would be unnecessarily sensitive.

One of the applications shown in figure 15.8 may come as a surprise to some readers; this shows the simple plane mirror reflective properties of a blazed reflective diffraction grating. The fringes show the errors in flatness of a wavefront that would form one of the multi-coloured slit images of the final spectrum if the grating were used in a spectrometer.

A modification of the Twyman-Green interferometer

The prime disadvantage of the Twyman-Green interferometer is that it requires reference optical components of the same size as the optical instrument that is being tested, so that if in diagram B of figure 15.8 one was testing a 150 mm aperture telescope objective, one would require a 150 mm diameter reference mirror, a 150 mm diameter retroreflector and an even larger beam splitter, all manufactured to the highest optical standards.

The simple transformation of the Twyman-Green interferometer shown in figure 15.10 more or less avoids these problems entirely, although the additional reference collimator lens has to be manufactured to interferometric standards; however, in view of its modest aperture, this is not a serious problem.

Just as many different optical configurations may be tested on the Twyman-Green interferometer, so too may a range of different optical devices be tested with

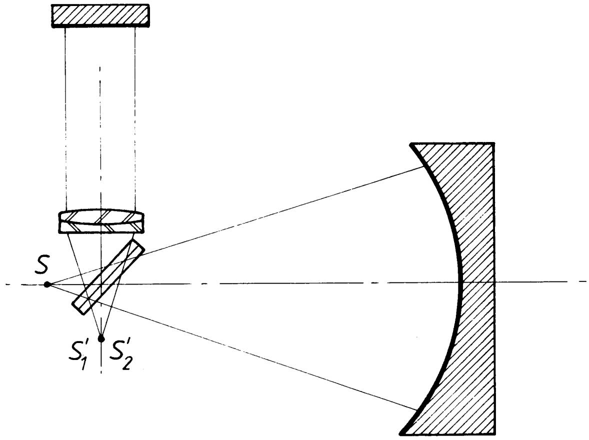


Figure 15.10 Modified Twyman-Green interferometer

this interferometer, but in this case each optical system must be arranged to image the source point back on to itself, which may or may not involve expensive additional reference surfaces. Clearly, the concave mirror being testing in the arrangement of figure 15.10 does not require any such additional reference surfaces, but the arrangements shown in figure 15.11 require a reference flat of a diameter that is big enough to cover the entrance pupil of the lens under test. An optical system set up so that it images a point back on itself in this way is referred to as being autostigmatic.

With the addition of a precision collimator of an appropriate aperture, all the configurations of figure 15.8 may be tested with an interferometer of this type. Modern versions also frequently make use of a laser source, which allows the reference path to be shorter than the test path, so allowing the construction of a compact instrument.

Laser sources, with their very high degree of monochromaticity, relax the requirement for the two beams of an interferometer to be of equal effective length, and for this reason laser sources are popular for workshop instruments because they reduce the time spent hunting for equality of path lengths, the operation which accounts for most of the time involved in adjusting an interferometer. Just because laser light is so coherent (monochromatic), laser-illuminated interferometers have to be carefully designed to avoid all pairs of surfaces in the reference and test arms forming fringes, which would clutter up the field of view with spurious fringes that contain no useful information.

Shearing interferometers

When an optical craftsman places an optical test plate in contact with the optical surface, he is polishing in more than one position; he is, in the language of

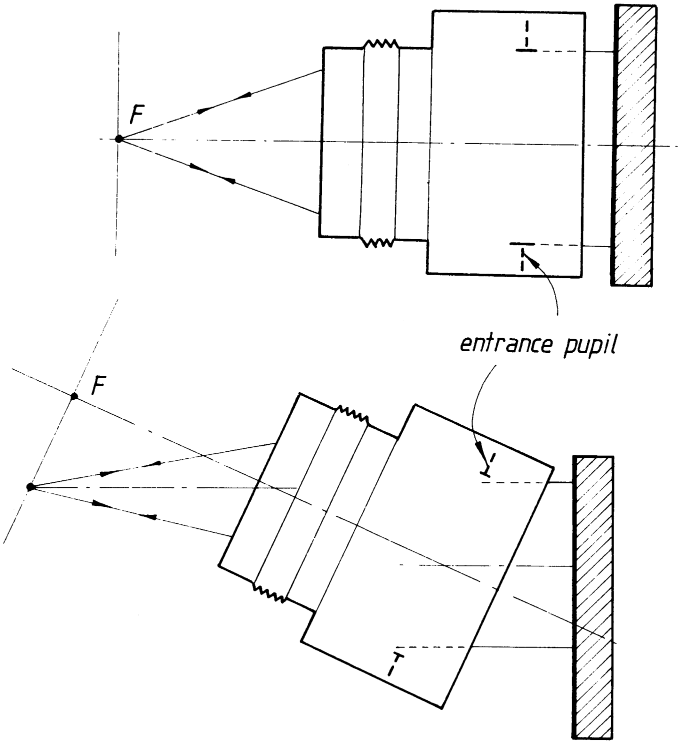


Figure 15.11 A photographic objective set up autostigmatically using a flat reference mirror

interferometry, 'shearing' the test plate against the surface being tested. If the surface being tested and the test plate fit each other perfectly in one position but neither surface is spherical, then the fringes that appear as the test plate is slid or 'sheared' over the test surface tell us what shape the two surfaces are, and this situation is a direct analogue of what happens in a shearing interferometer, where the test wavefront is sheared against itself to reveal any lack of sphericity.

The advantage of shearing interferometers is that they do not require to segregate a perfect reference wavefront in a separate reference arm; as the shearing is performed after the wavefront has traversed the optical system, these instruments can be remarkably compact, stable and insensitive to vibration.

Their disadvantage is that the fringes are not a direct contour map of the wavefront shape, but instead a contour map of the difference between the two identical replicas of the test wavefront. This can be a severe disadvantage in the routine workshop testing of small or medium sized optical components or systems, but for large astronomical mirrors the stable and quantitative nature of the information provided offers advantages over the knife edge or Hartmann test that might otherwise be employed.

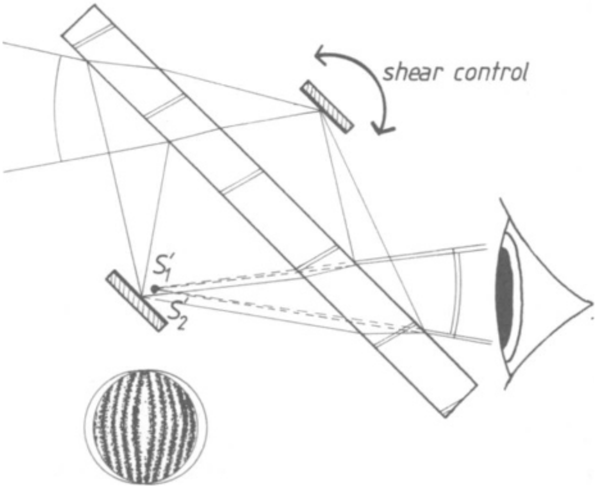


Figure 15.12 Shearing interferometer

Figure 15.12 shows the construction of a typical shearing interferometer as devised by W. J. Bates and R. L. Drew of Bristol University in the 1940s, and applied so successfully by D. S. Brown of the Grubb Parsons Company to the testing of large telescopes. Figure 15.13 shows the identical wavefront shearing effect produced by a diffraction grating, which may again be used for testing optical systems, in which case it is known as the Ronchi test.

Just as in the other interferometers we have discussed, in both these shearing interferometers two images of the source are formed and the adjustment of the interferometer consists in superimposing the two images and searching for equality of optical path in the two beams of light. In the case of the Ronchi test the equality of path length is more or less built-in and the separation of the images is adjusted by moving the grating longitudinally until the focus of the pencil to be tested is at the plane of the grating. For the Bates–Drew–Brown interferometer the images are adjusted for coincidence by moving the instrument along the optical axis, and the equality of path is achieved by a transverse motion of the instrument.

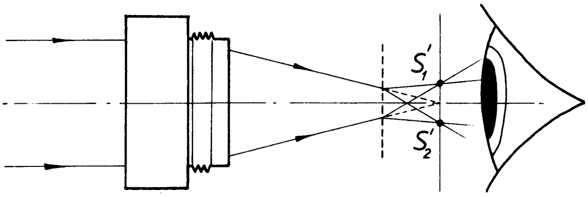


Figure 15.13 The Ronchi test

Common path interferometers

If the reference beam in figure 15.10 could be made to traverse the same path as the test beam, but with a much reduced aperture, the two beams would automatically have the same path length and, as long as the aperture of the reference beam was small enough at the pupil of the optical system being tested, it would not pick up any aberrations and so would be suitable to generate a reference wavefront.

This is the principle on which a number of so-called common path interferometers operate, and figure 15.14 shows the schematic layout of J. M. Burch's scatter plate common path interferometer, which is a particularly elegant example of this type of instrument.

In the scatter plate interferometer a point source is imaged into the pupil of the optical system through a fine diffuser, so that approximately 50 per cent of the light is scattered to fill the aperture of the system under test. The scattering diffuser is imaged by the lens on to another identically replicated or mirror image replicated scattering surface, so that the image is in precise register. The pupil of the optical

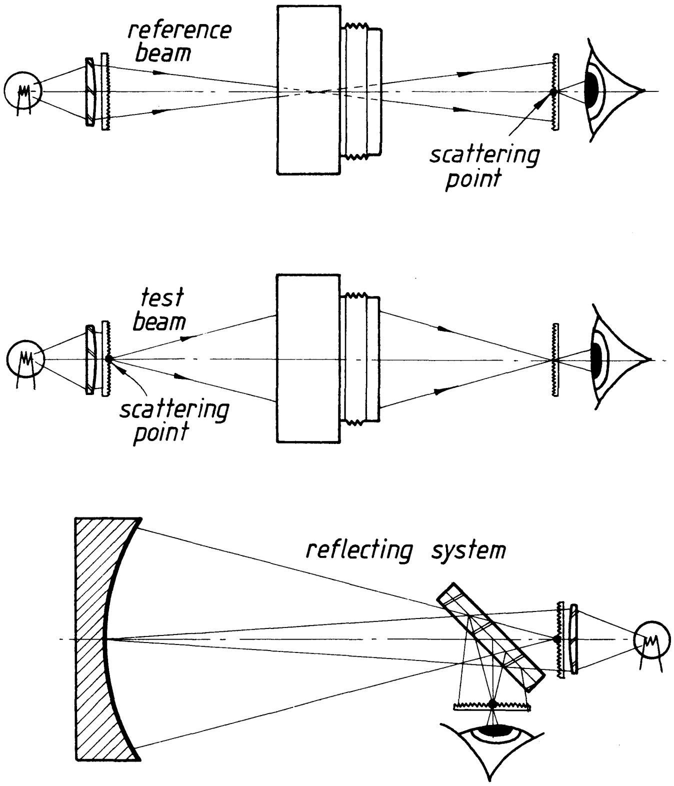


Figure 15.14 J. M. Burch's scatter plate interferometer

system is then viewed through the second diffuser and the direct-diffused reference beam interferes with the diffused-direct test beam to give an interferogram of the aberrations of the test pupil. By diffused-direct we refer to that light that is scattered by the first diffuser and not scattered by the second diffuser. Similarly, direct-diffused light is not scattered by the first diffuser but is scattered by the second diffuser.

The advantages of a scatter plate interferometer are that we can locate the precise position of the scattering surfaces and thus make metrologically sound measurements on the position of the focal plane of the optical system. The instrument can also be used with a white light source, of any chosen waveband, to measure chromatic aberrations, and the scattering components may also be made inexpensively.

A great deal of ingenuity has been applied to the design of alternative common path interferometers, some using birefringent optical elements, some using beam splitting prisms and so on, but the principle of generating a reference beam by differential beam splitting at the object end of the optical path remains the same, and the resulting interferogram remains the same: a direct contour map of wavefront shape.

Although the reference and test beams follow the same optical path in a common path interferometer, so that there is a certain degree of compensation for vibration and other disturbances, the compensation is not particularly effective because the beam splitting takes place at the beginning of the optical path. The two beams therefore traverse the optical system in a differentiated state, so picking up significant effects from most sources of disturbance. This compensation is almost complete in the simple shearing interferometer and, for this reason, it still holds pride of place for testing large optical systems such as astronomical telescopes.

The point diffraction interferometer

An interferometer that combines the post-aberration formation stability characteristics of the shearing interferometer with the interferogram interpretation advantages of the normal Twyman-Green or common path interferometers, together with the metrological convenience of the scatter plate interferometer, is the point diffraction interferometer shown in figure 15.15.

This interferometer was first invented by the Russian optician W. P. Linnik in 1933, but it has been the subject of extensive reinvestigation by R. N. Smartt during the 1970s.

The principle of the interferometer could hardly be less complicated: it consists of a pin hole in a semi-transparent film deposited on a glass plate. The pin hole is arranged to be smaller than the detailed structure of the diffraction pattern at the focus of the pupil under investigation, so that it can generate an independent, smooth reference wavefront, against which the test wavefront can be compared. In particular, in the case of a perfect wavefront, the central maximum of the diffraction pattern has a diameter of $1.22\lambda \div (n' \sin u')$, so that, for an $f/5$ lens

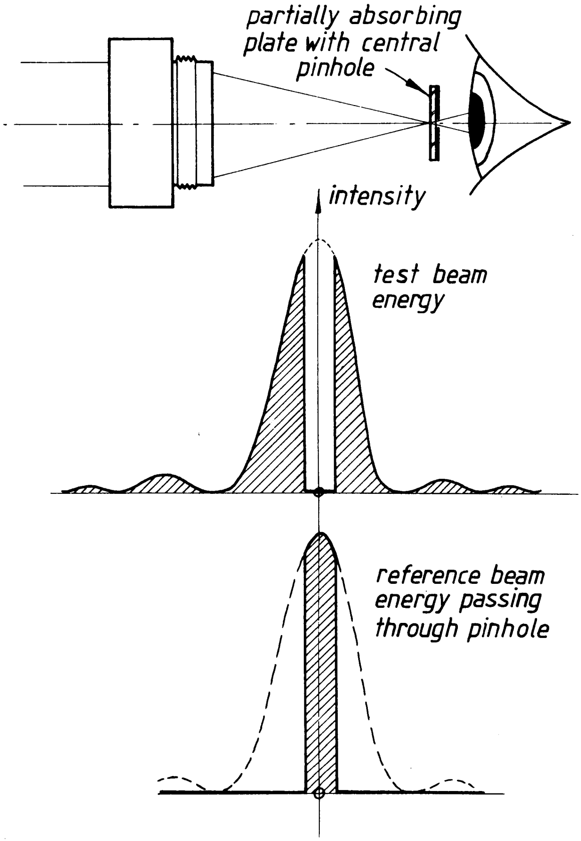

partially absorbing plate with central pinhole
intensity
test beam energy
reference beam energy passing through pinhole

Figure 15.15 The point diffraction interferometer

forming a visual image in air, the reference pin hole must be smaller than 0.006 mm in diameter.

Not only must the pin hole be smaller than the central maximum of the diffraction pattern but it should also be of such a size that the reference wavefront and the test wavefront entering the observer's eye both have the same intensity. Thus, if the semi-transparent film has a transmission factor of 10 per cent, the pin hole should have a diameter of 16 per cent of the central maximum, or approximately 0.001 mm in our example. For systems with aberrations, more energy is diffracted into the outer regions of the diffraction pattern and the pin hole can usefully be increased in diameter.

Just as in other two beam interferometers, tilt fringes can be introduced into the interferogram by moving the pin hole sideways, and circular defocus fringes can be introduced by moving the pin hole along the optical axis. The pin hole operates exactly as though it is a reference image of the point source, so that the interferogram is formed on the observer's retina in exactly the same way as in the double pin-hole interferometer of figure 15.1, or any of the other two beam interferometers that we have considered.

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